Extensive Deposits on the Pacific Plate from Late Pleistocene North American Glacial Lake Outbursts

William R. Normark and Jane A. Reid[1]

U.S. Geological Survey, Menlo Park, California 94025, U.S.A.
(e-mail: wnormark@usgs.gov)

ABSTRACT

One of the major unresolved issues of the Late Pleistocene catastrophic-flood events in the northwestern United States (e.g., from glacial Lake Missoula) has been what happened when the flood discharge reached the ocean. This study compiles available 3.5-kHz high-resolution and airgun seismic reflection data, long-range sidescan sonar images, and sediment core data to define the distribution of flood sediment in deepwater areas of the Pacific Ocean. Upon reaching the ocean at the mouth of the Columbia River near the present-day upper continental slope, sediment from the catastrophic floods continued flowing downslope as hyperpycnally generated turbidity currents. The turbidity currents resulting from the Lake Missoula and other latest Pleistocene floods followed the Cascadia Channel into and through the Blanco Fracture Zone and then flowed west to the Tufts Abyssal Plain. A small part of the flood sediment, which was stripped off the main flow at a bend in the Cascadia Channel at its exit point from the Blanco Fracture Zone, continued flowing more than 400 km to the south and reached the Escanaba Trough, a rift valley of the southern Gorda Ridge. Understanding the development of the pathway for the Late Pleistocene flood sediment reaching Escanaba Trough provides insight for understanding the extent of catastrophic flood deposits on the Pacific plate.

Introduction

The catastrophic effects of the Late Pleistocene floods on the landscape of central Washington are well documented (e.g., Bretz et al. 1956; Baker 1973; Waitt 1980, 1985; Baker and Bunker 1985; Atwater 1986; Baker et al. 1991) and continue to be the subject of many ongoing studies. However, surprisingly little recent work has been done to determine what happened once the floods entered the Pacific Ocean from the Columbia River. It was generally accepted that flood sediment probably entered the Willapa and Astoria submarine canyons, which head near the mouth of the Columbia River and lead, respectively, to the Cascadia Channel and the Astoria submarine fan (fig. 1). Much of the sediment might eventually reach the deep-sea floor as a result of marine resedimentation processes. One study specifically suggested that sediment from Late Pleistocene glacial floods reached the Pacific plate through the Cascadia Channel (Griggs et al. 1970). Sediment recovered at Deep Sea Drilling Program (DSDP) site 35 (fig. 1, *inset*) indicated that the upper few hundred meters of the fill in the Escanaba Trough segment of the southern Gorda Ridge probably came from the Columbia River drainage area (Shipboard Scientific Party 1970; Vallier 1970; Vallier et al. 1973; Normark et al. 1994; Zuffa et al. 1997).

Later scientific drilling in the Escanaba Trough not only confirmed that the source of the turbidite sediment fill was consistent with that from the Lake Missoula floods but also further indicated that deposition occurred in the latest Pleistocene (Brunner et al. 1999; Zuffa et al. 2000). Because the Escanaba Trough is nearly 1000 km from the Columbia River, Zuffa et al. (2000) proposed that the glacial lake flood waters continued flowing as hyperpycnally generated turbidity currents upon reaching the ocean (Mulder and Syvitski 1995).

Goldfinger et al. (2000) showed that the giant Heceta submarine slide at about 110,000 yr ago blocked the Astoria Channel and prevented southward transport of sediment along the base of the continental slope (fig. 1). In addition, Wolf et al. q1

Manuscript received June 28, 2002; accepted July 1, 2003.

[1] U.S. Geological Survey, Santa Cruz, California 95060, U.S.A.

(1999) showed that the Astoria Channel south of the Heceta slide is no longer active and is partially filled by hemipelagic sediment. Coincidentally, Zuffa et al. (2000) had concluded that the turbidity-current pathway to the Escanaba Trough was probably along the Cascadia Channel and then to the south after reaching the Pacific plate. If this interpretation is correct, then a significant part of the glacial lake flood sediment must have continued flowing in the Cascadia Channel, reaching the Tufts Abyssal Plain perhaps as much as 1000 km farther west.

The purpose of this study is to (1) document the proposed Pacific plate pathway and depositional areas for the Late Pleistocene flood deposits, including those found in Escanaba Trough, (2) evaluate the extent (including volume) of Late Pleistocene Lake Missoula flood deposits on the Pacific plate, and (3) briefly examine the extent of Pleistocene turbidite deposition on the Pacific plate, including the Tufts Abyssal Plain.

Geologic Setting and Previous Work

Figure 1, based on the concluding figure of Zuffa et al. (2000), shows that the Cascadia Channel extends across the young Juan de Fuca plate from the continental slope off the Columbia River and enters the Blanco Fracture Zone (BFZ). The channel marks the northern and western limit of the Astoria Fan and acts as a runoff gutter collecting turbidity currents that cross the fan. The Cascadia Channel exits the BFZ onto the Pacific plate and leads directly to the Tufts Abyssal Plain just west of long 129°W (fig. 1). Hurley (1960, 1964) recognized that the Tufts Abyssal Plain was fed by the Cascadia Channel and suggested that the channel extends nearly 1500 km farther west after exiting the BFZ.

The Tufts Abyssal Plain remains poorly defined today. Using the limited seismic reflection data available, Winterer (1989) showed several extensive areas with a sediment thickness of more than 400 m within the boundaries of the plain as mapped by Hurley (1964). On the basis of rather limited sediment core data, Moore (1989) indicated that about half of the samples from the Tufts Abyssal Plain contain some "terrigenous" material, generally clay and silt-sized nonbiogenic sediment. Most of the data available for this study is from the Cascadia Channel and the Tufts fan (informally named).

The key to understanding turbidite sedimentation on the eastern Pacific plate was provided by drilling at site 1037 in the Escanaba Trough during Ocean Drilling Project (ODP) Leg 169 (Shipboard Scientific Party 1998), which recovered more than 500 m of turbidite deposits that can be used to provide ground truth for interpretation of high-resolution seismic reflection data. On the basis of the petrology of the sand beds cored at site 1037, Zuffa et al. (2000) determined that the bulk of the Escanaba Trough fill is from the Columbia River and not the adjacent California margin (fig. 1). The upper 120 m of sandy turbidites from site 1037 is younger than 16 Ka, and much of it is coincident in age with the Missoula Floods (Brunner et al. 1999). A sequence of 10 turbidite beds (not counting small events generated locally) was sampled in the upper 63 m of the hole (fig. 2; Zuffa et al. 2000). This upper sequence of beds, the thickest of which is 12 m, is underlain by one extremely thick (57 m) sand interval interpreted as one turbidite bed; this bed overlies a muddy interval dated at 15.48 Ka (Zuffa et al. 2000). These 11 turbidite beds, nearly 120 m of sediment, were interpreted to be the result of turbidity currents generated by the Lake Missoula flood events. Even if this interpretation is correct, these deposits in the Escanaba Trough cannot be the complete record of the flood events as documented on land (Waitt 1980, 1985, 1994; Baker and Bunker 1985; Atwater 1986; Shaw et al. 1999; Clague et al. 2003) but represent only the largest flows to reach the Escanaba Trough.

Turbidite beds younger than 15.7 Ka can be found throughout the Escanaba Trough in water depths >3100 m (note the similarity of the high-resolution profiles in fig. 2 and the airgun profiles in fig. 3; see also Normark and Serra 2001). The turbidity currents that enter Escanaba Trough from the south are trapped; as a result, all the sediment in suspension within the flows is deposited, producing thick beds that show the same relative spacing of reflectors throughout the trough. Figure 2 shows that the reflections generally mark the top of the sandiest interval in each graded turbidite. The thickness of any given turbidite bed is a function of the water depth at the time of deposition (Normark et al. 1997; Normark and Serra 2001). This relationship reflects the decreasing volume of suspended sediment with increasing height above the base of the turbidity current flow (fig. 2*A*; fig. 3*B*, 3*C*). The bed thickness and water depth data of Normark and Serra (2001) can be used to determine the height (water depth to the tops of the flows) of the turbidity currents that entered the Escanaba Trough (table 1). There are sufficient data for beds B through H of the upper sequence to be able to project the upper boundaries of the associated turbidity currents to range between 3126 and 3194 m. Normark and Serra (2001) further demonstrated that q2

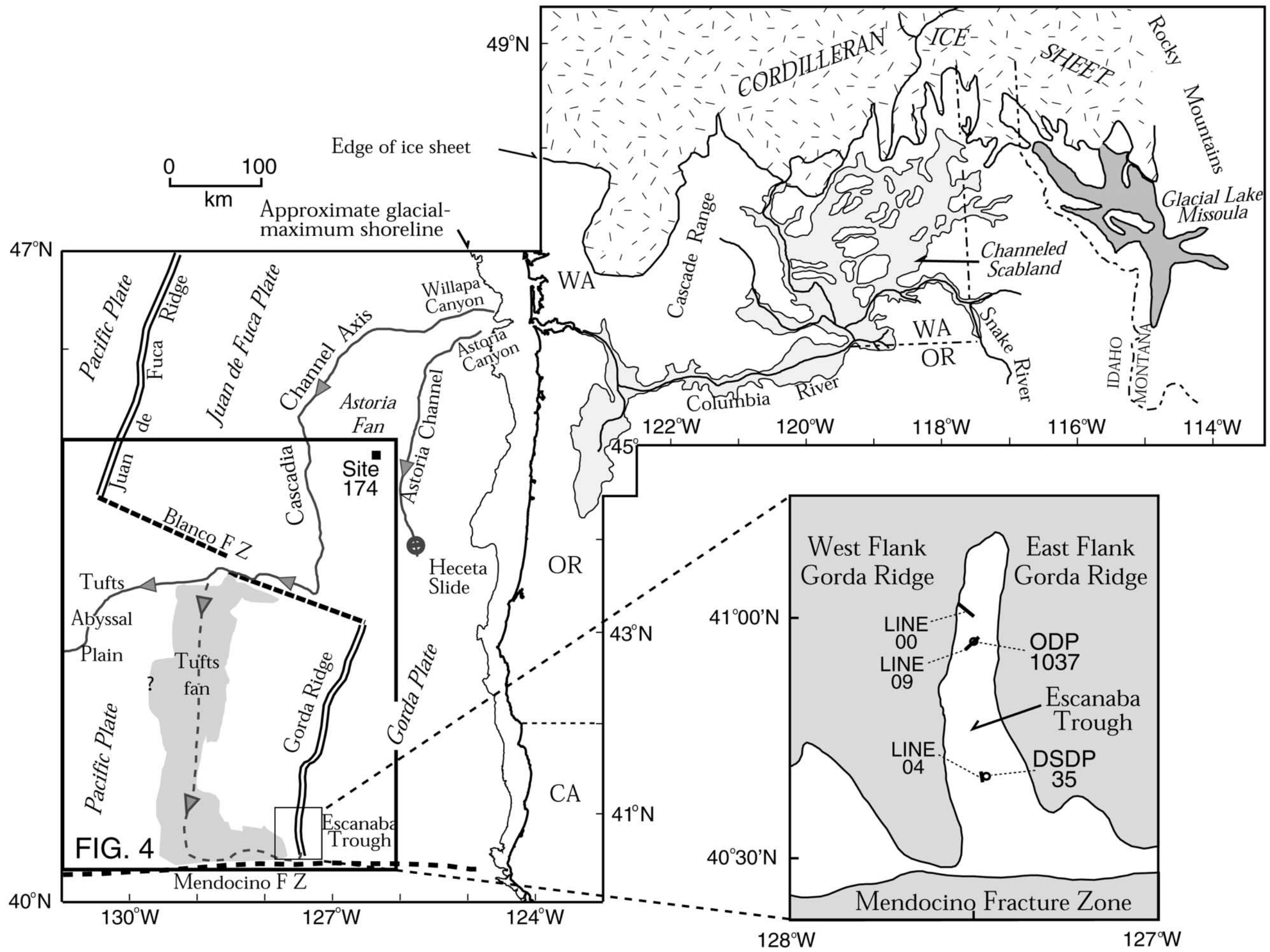


Figure 1. Schematic map showing path of Late Pleistocene flood sediment that moves through the Cascadia Channel to the Tufts Abyssal Plain (*solid line*) and to the Escanaba Trough (*dashed line*) through the Blanco Fracture Zone (modified from Zuffa et al. 2000). Darker gray shaded area is approximate limit of the Tufts fan (Reid and Normark, in press). Rectangle shows location of figure 4. Small inset (*lower right*) gives the location of Deep Sea Drilling Program (*DSDP*) and Ocean Drilling Project (*ODP*) drill sites and the high-resolution 4.5-kHz profiles of figure 2. Light gray shading in Washington and Oregon shows extent of Late Pleistocene onshore floods for comparison.

many of the oceanic crustal fault offsets in the seismic reflection profiles have not been active since deposition of turbidites younger than 15 Ka.

The sediment log for site 1037 shows that sandy turbidite deposits are common to about 510 m below the sea floor (mbsf). Thick beds of sand similar to the upper 60 mbsf occur only in the interval from 142 to 177 mbsf. Between 177 and 355 mbsf, sand beds are thinner and less common, but below this interval to 510 mbsf, sand beds are again common (fig. 3).

Attempts to date the sediment below 316.9 mbsf (the deepest reported by Brunner et al. 1999) have been unsuccessful because of a lack of preserved carbonate material (M. McGann, written communication, 2002), probably as a result of hydrothermal fluids moving through the sequence. Extrapolation of the sediment rates obtained by Brunner et al. (1999) for the interval 262.3–316.9 mbsf suggests that the earliest turbidites arrived at the drill site at about 55 Ka. This sedimentation rate, which is for dominantly muddy sediment, is the slowest observed at site 1037 below the Holocene; hence the age of the oldest turbidite is probably younger. All of the turbidite fill sampled at site 1037 thus postdates the Heceta slide event and is the record of only the latest Pleistocene (<55 Ka). To distinguish the latest Pleistocene turbidite fill of Escanaba Trough from the proposed Lake Missoula flood deposits above 120 mbsf at site 1037, the lat-

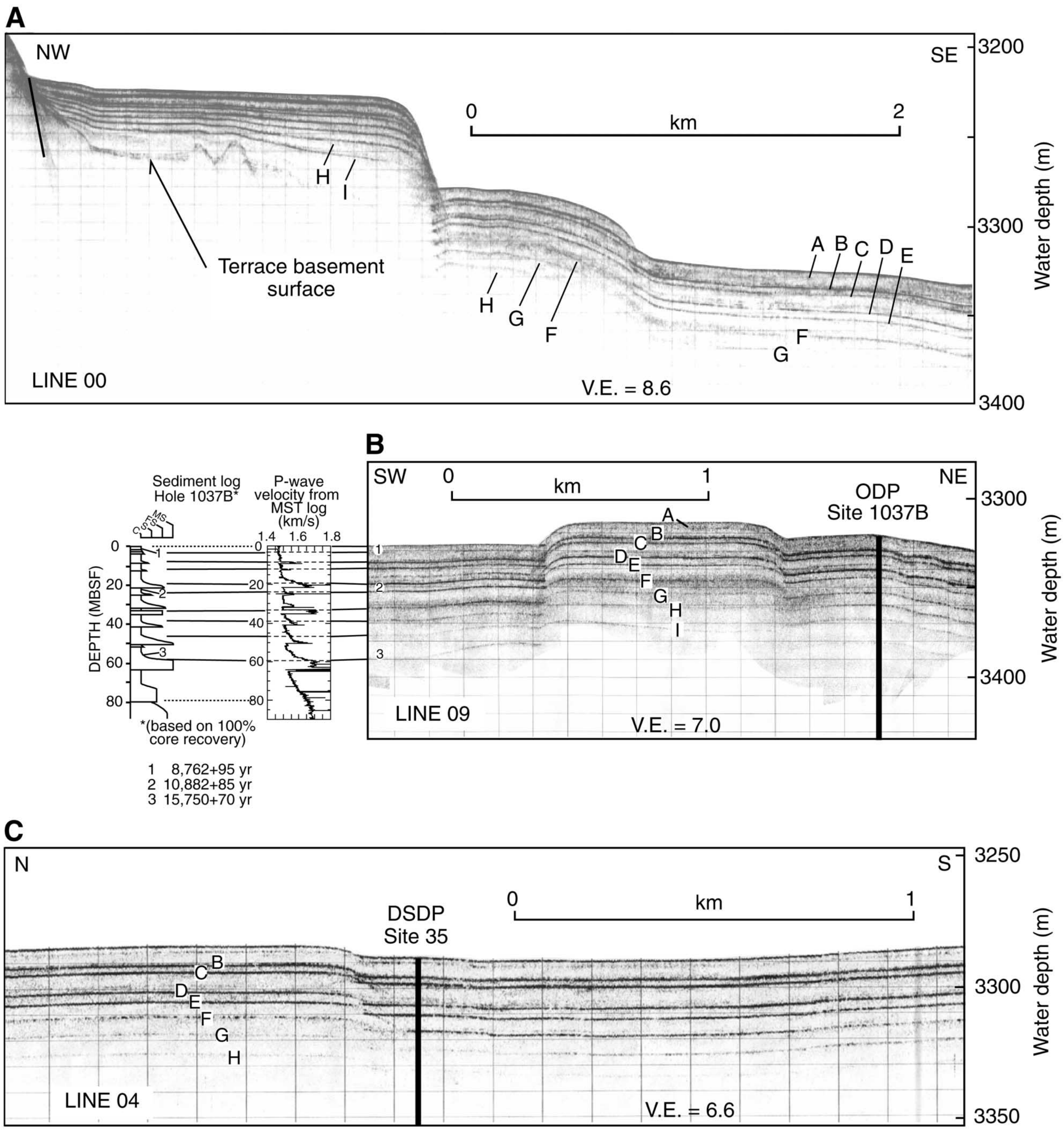


Figure 2. Deep-tow 4.5-kHz profiles showing the characteristic spacing of turbidite reflectors in the Escanaba Trough. *A*, Line 00 from the northern part of the Escanaba Trough shows that the spacing between reflections increases with increasing water depth. *B*, Line 09 shows the reflector sequence at Ocean Drilling Project (*ODP*) hole 1037B and the correlation with the sediment log and with the P-wave velocity log. *C*, Line 04 from southern part of the Escanaba Trough near Deep Sea Drilling Program (*DSDP*) site 35 shows the same reflector sequence. Adapted from figures 5 and 6 in Zuffa et al. (2000). Location of DSDP and ODP drill sites profiles shown in figure 1.

ter will be referred to as late (isotope) stage 2 deposits following the isotope time scale of Martinson et al. (1987).

Data

The sea floor west of the Gorda Ridge was surveyed to the limit of the 200-nautical-mile (370 km) Exclusive Economic Zone (EEZ) during the GLORIA (Geological LOng-Range Inclined ASDIC [Anti-Submarine Detection Investigation Committee]) surveys of 1984 (EEZ-SCAN 84 Scientific Staff 1986). These surveys provided uniformly spaced, east-west transects of the west flank of the ridge. In addition to the GLORIA side-looking sonar image of the sea floor, the surveys also obtained airgun seismic reflection profiles and high-resolution 3.5-kHz profiles (fig. 4). A multichannel seismic reflection survey of the southern Juan de Fuca Ridge and southern Gorda Ridge also obtained 3.5-kHz seismic reflection profiles. The remaining data consist of 3.5-kHz profiles obtained during transits to and from the southern Juan de Fuca Ridge in support of the USGS hydrothermal mineral program. These tracklines form a fan-shaped spread with the apex just north of the study area for this article (fig. 4); the higher speed during these transit legs resulted in high vertical exaggeration of these profiles.

Our interpretations are based on seismic reflection data from nine surveys conducted between 1980 and 1985. More than 4000 trackline kilometers of seismic reflection data are available for this compilation. Position control for all of the cruises was based on transit satellite data. Limited amounts of recent multibeam echo-sounding data were reviewed to check interpretations on the influence of oceanic-ridge flank topography on turbidite sedimentation. Sediment core samples from the study area are limited in number but are sufficient to confirm widespread deposition of terrigenous sediment on the Pacific plate. In addition, the water depth range of the cores that contain terrigenous silt and clay is consistent with that observed in the Escanaba Trough.

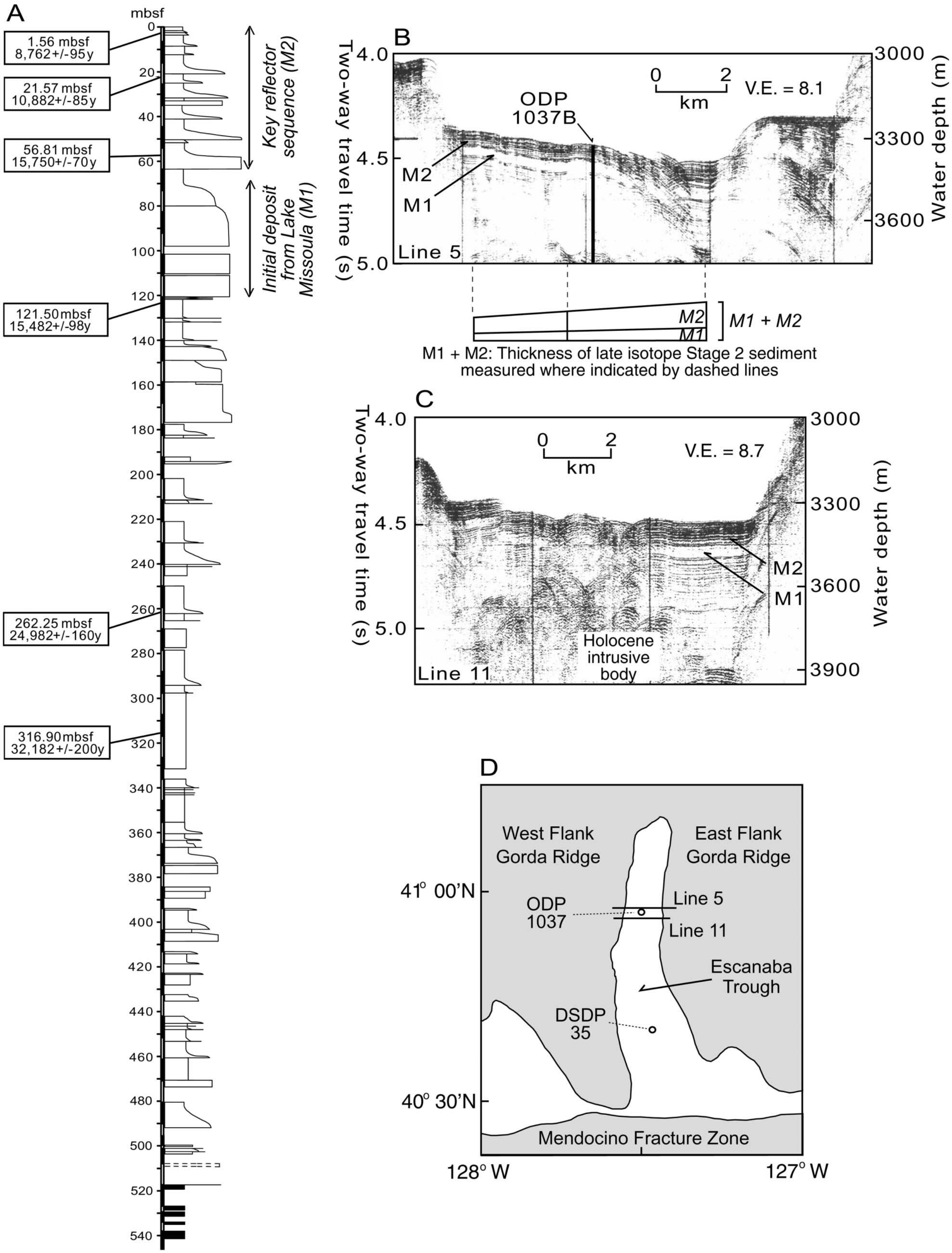
Cascadia Channel and Tufts Submarine Fan

The sediment sequence in the Escanaba Trough is a record of only the largest turbidity current events during the last ~55 Ka and, as such, does not provide a full record of even the late stage 2 events deposited on the Pacific plate. We examine the submarine pathway for the Late Pleistocene flood deposits to reach the Escanaba Trough to gain insight on the probable extent of Pleistocene glacial lake flood deposits on the Pacific plate. The Cascadia Channel, which does not extend to the Escanaba Trough, has fed a large submarine fan that extends 400 km between the two.

Cascadia Channel. Cascadia Channel extends offshore from the Willapa Canyon near the mouth of the Columbia River (fig. 1). Hurley (1964) suggested that the channel extends about 2300 km from the base of the continental slope, although its extension farther than 1800 km is not clear (fig. 5). Later studies were generally limited to the proximal 700 km of the channel, that is, to the area upstream from where the channel exits from the Blanco Fracture Zone (BFZ; Griggs and Kulm 1970*a*, 1970*b*, 1973; Embley 1985). Cascadia Channel is deeply eroded where it approaches the BFZ, and all seismic reflection profiles (to the western limit of the study area at long 131°W) that cross the channel show truncation of reflectors that have an acoustic character typical of turbidite deposition. Channel relief is generally about 200 m or greater (fig. 6*D*; Reid and Normark, in press).

Embley (1985) obtained multibeam sounding data that showed that the Cascadia Channel makes abrupt, nearly 90° bends not only where it enters and exits the BFZ, but also where it steps from the northern to the southern side of the fracture zone trough (fig. 4). Despite the sharp bends, the longitudinal profile of the Cascadia Channel in BFZ shows that its thalweg has a smoothly changing gradient from the southern Juan de Fuca plate to near its exit from the BFZ (fig. 5). Just upstream from its exit from the BFZ, there is an abrupt notch in the axial profile where a small rift valley has formed by spreading within the BFZ (deCharon 1986).

Deposition within Cascadia Channel is typical of many modern turbidite systems, showing a change to more clay-rich sediment during the Holocene as more coarse sediment is trapped on the shelf (Griggs and Kulm 1970*b*, 1973). Nelson et al. (1988) were able to use the 6.9-Ka Mazama ash present in sandy turbidite beds to demonstrate that the Cascadia Channel was active well after 5 Ka. There is a marked change in sediment grain size, however, between Late Pleistocene and Holocene deposits in Cascadia Channel. Griggs et al. (1970) described coarse-grained (to gravel-sized) sediment from three localities within the proximal 750 km of Cascadia Channel. One sample was from the channel on the south side of the BFZ (core C3; table 2; fig. 4). Griggs et al. (1970) showed that the lithologies of pebbles in these gravel beds were consistent with rock types transported by the Colum-


A
mbsf
1.56 mbsf
8,762+/-95y
21.57 mbsf
10,882+/-85y
56.81 mbsf
15,750+/-70y
121.50mbsf
15,482+/-98y
262.25 mbsf
24,982+/-160y
316.90mbsf
32,182+/-200y
Key reflector sequence (M2)
Initial deposit from Lake Missoula (M1)
B
Two-way travel time (s)
Water depth (m)
ODP
1037B
V.E. = 8.1
km
M2
M1
Line 5
M1 + M2
M1 + M2: Thickness of late isotope Stage 2 sediment
measured where indicated by dashed lines
C
V.E. = 8.7
Holocene
intrusive
body
Line 11
D
West Flank
Gorda Ridge
East Flank
Gorda Ridge
41° 00'N
ODP
1037
Line 5
Line 11
Escanaba
Trough
DSDP
35
40° 30'N
Mendocino Fracture Zone
128° W
127° W

bia River and its tributaries. Conclusive ages for the gravel layers were not available, but the authors speculated that the deposits were brought to the ocean by Late Pleistocene glacial floods.

Other core samples on the north side of the Cascadia Channel document that terrigenous sediment deposition occurred in latest Pleistocene. Core C1 (table 2; fig. 4) recovered 9.75 m of "late Pleistocene" terrigenous sediment at 3175-m water depth in the area of flow-stripped deposition that lies 50 km west of the exit of the Cascadia Channel from the BFZ (Duncan et al. 1970; Reid and Normark, in press). Carbon 14 dates gave 15.9 Ka at a 2.3-m depth in this core and 27.2 Ka at a 5.8-m depth, suggesting multiple depositional events of terrigenous sediment during the latest Pleistocene. Core C2 (table 2; fig. 4), on the northern overbank area of the Cascadia Channel on the Pacific plate about 20 km west of the channel floor core described by Griggs et al. (1970), recovered terrigenous sediment at a 3334-m water depth dated at about 8.5 Ka (after the last turbidity current reached Escanaba Trough; fig. 3).

Tufts Fan. Tufts fan, named after the adjacent Tufts Abyssal Plain (Hurley 1960), is defined herein as the turbidite system that extends southward from the Cascadia Channel to the Mendocino Fracture Zone (MFZ; fig. 4). Figure 4 shows that the Cascadia Channel forms the northern limit of the Tufts submarine fan along a 60-km reach downstream of its exit from BFZ. The Tufts fan is fed by overflow from the southern edge (left-hand, looking downstream) of the channel. There is a broad and low relief feeder channel that extends a short distance from the Cascadia Channel, and the fan has a convex upward cross section near its apex (figs. 6*A*, 7). The right-hand (looking downstream) levee of the feeder channel has both large-scale and small-scale sediment waves, typical of deep-sea turbidite channel levees (Normark et al. 2002; Reid and Normark, in press).

The southern edge of the Cascadia Channel margin is about 170 m above its thalweg, where it trends westerly from the BFZ exit (fig. 5). The water depth along the southern overbank area of the Cascadia Channel is between 3190 m and 3220 m in the area of the Tufts fan. Thus, as shown by the depth to the tops of the turbidity currents that reached the Escanaba Trough (fig. 6*A*; table 1), only the largest turbidity currents moving through the Cascadia Channel could overflow along this reach of the channel.

Table 1. Thickness of Key Turbidite Beds in the Escanaba Trough and Water Depth at Time of Deposition of Each Bed

Bed ID	Bed thickness, sand/silt only (m)	Sand and silt to clay (%)	Bed thickness, all grain sizes (m)	Top of turbidity current (m)
B	1.5	31	4.8	3173
C	1	26	3.9	3194
D	5	56	8.5	3136
E	2	55	3.6	3188
F	4.5	67	6.7	3165
G	6	79	7.6	3144
H	5	55	9	3126

Note. Water depth after deposition of bed I is used to correlate with the thickness of bed H, and so forth. Based on data presented in Normark and Serra (2001).

The Tufts fan thus receives sediment by "normal" overbank deposition that commonly forms levees along turbidite channels. Perhaps more important, however, where the Cascadia Channel has sharp bends, the upper part of the turbidity current that exceeds the channel depth continues to flow in the direction it was moving before entering the bend. This process is known as flow stripping because the upper part of the turbidity current is separated from the flow remaining in the channel (Piper and Normark 1983). Flow stripping is a special case of overbank deposition adjacent to turbidite channels; but for the Tufts fan, this process is a major point source as sediment is stripped off where the channel turns west upon exiting the BFZ.

Just upstream from the Tufts fan where the Cascadia Channel turns south toward its exit from the BFZ, substantial flow stripping has resulted in deposition of as much as 500 m of sediment in a deep, 100-km-long trough between high ridges of the western BFZ (see fig. 6 in Reid and Normark, in

Figure 3. *A*, Sediment log for Ocean Drilling Project (*ODP*) hole 1037B in the Escanaba Trough (modified from Zuffa et al. 2000). Vertical scale is in meters below the sea floor (*mbsf*). The width of the sediment log is proportional to grain size, which ranges from clay (*thinnest*) to medium sand (*thickest*). *B*, *C*, Airgun source seismic reflection profiles that cross the Escanaba Trough near ODP site 1937 (excerpted from fig. 3 in Davis and Becker 1994). *D*, Map showing location of profiles in *B* and *C*. Bar graph between *B* and *C* shows lateral thickness variation of units *M1* and *M2* in *B*.

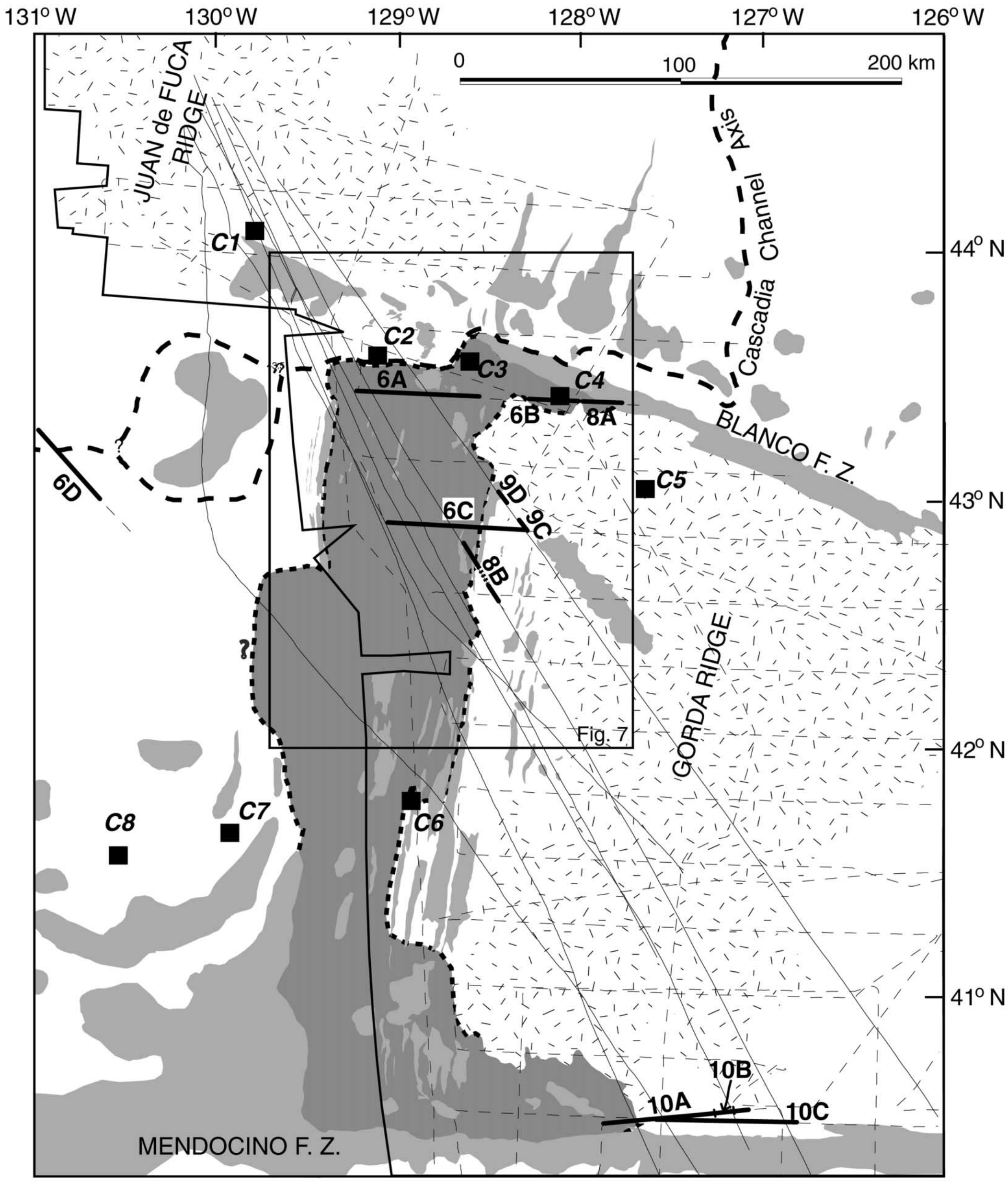


Figure 4. Map of study area showing the western limit of GLORIA (Geological LOng-Range Inclined ASDIC) side-looking sonar image (*heavy irregularly stepped solid line*) and all tracklines for seismic reflection data. Thin dashed lines show cruises that obtained 3.5-kHz high-resolution reflection profiles as well as single or multichannel seismic reflection data using airgun sound sources. Thin solid lines indicate 3.5-kHz data only. Stippled area indicates area dominated by the topographic relief of the Gorda and Juan de Fuca Ridges. Darker shading indicates area of the Tufts fan. The heavier shading indicates high relief of the Blanco and Mendocino Fracture Zones in addition to higher-standing basement relief, which is typically surrounded by sediment-smoothed sea floor. Locations of the seismic reflection profiles in figures 6 and 8–10 and the area of the GLORIA image of figure 7 are shown. Core locations shown by squares; see table 2.

press) and filled smaller basins in the rugged topography on the Pacific plate between the channel and the BFZ. The present seafloor water depths of the turbidite deposits that lie north and west of the Cascadia Channel are generally between 3200 m and 3275 m, well within reach of the turbidity currents that made it to the Escanaba Trough (table 1).

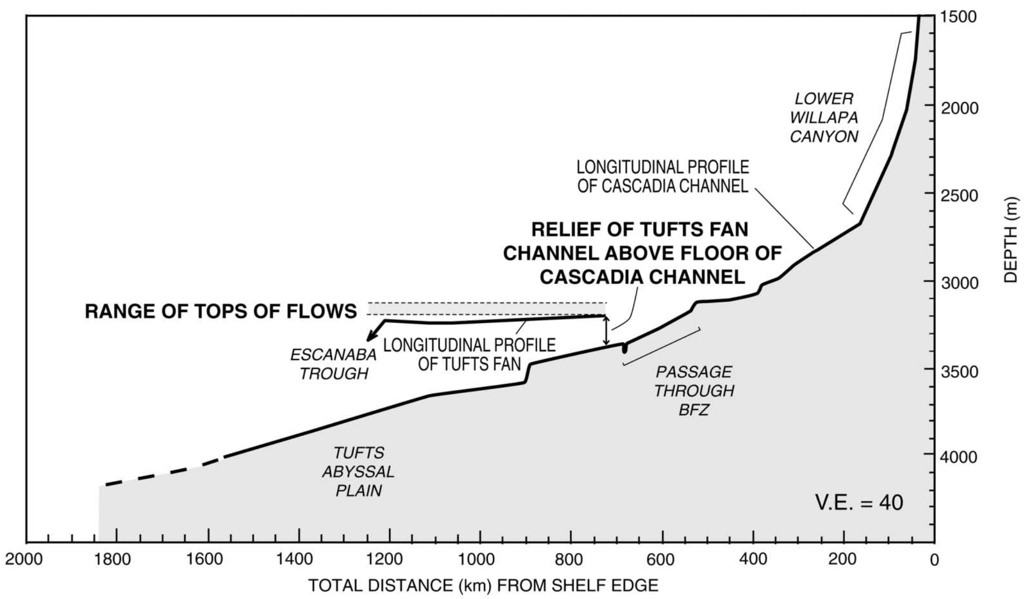


Figure 5. Longitudinal profiles of the Cascadia Channel (data from Griggs and Kulm 1970*a*; Embley 1985; Grim et al. 1992) and the Tufts fan (Reid and Normark, in press). The tops of the turbidity currents as measured in the Escanaba Trough are shown for reference.

The eastern edge of the Tufts fan generally trends north-south and is characterized by turbidite deposition onlapping and ponding between basement ridges on the western flank of the Gorda Ridge (fig. 7). In the northeast corner of the Tufts fan, sediment has ponded in a deep basin south of a high BFZ ridge (figs. 6*B*, 7). A 3.5-kHz record from the eastern part of the profile in figure 6*B* shows an acoustic character similar to the sequence of reflectors in the Escanaba Trough (reflectors B to I; fig. 8*A*). The western edge of the fan is bounded by prominent north-south-trending ridges, except between about lat 42°N and 42°45′N where there are insufficient bathymetric data to resolve the fan boundary and to identify possible additional topographic barriers (figs. 4, 7).

q3 The Tufts fan is generally atypical of submarine fans because its sediment source consists only of overbank flow from a deep channel and because the flows forming the fan can spread laterally only a limited distance before becoming confined by basement ridges on the flank of the Gorda Ridge (fig. 7). As a result, the morphology of the fan is subdued. Distributary channel features are limited to the fan north of lat 42°30′N and are more common in the western part of the fan (fig. 7). Many of the small channel forms in the high-resolution 3.5-kHz profiles might be scour features commonly seen in sandy lobe deposits on modern turbidite systems (Piper et al. 1999). In cross section, the fan appears ponded in most profiles (e.g., fig. 6*C*). The fan's longitudinal profile shows very low relief over the 400 km from the Cascadia Channel to the Escanaba Trough (fig. 5). The Tufts fan exhibits the basic elements of many submarine turbidite systems, including small channels and lobe features on the middle fan, a gently sloping lower fan, and a large ponded basin plain equivalent. The elements and growth pattern of the Tufts fan are described in Reid and Normark (in press), with more extensive presentation of seismic reflection data to define the fan elements. The GLORIA sidescan image of figure 7 shows isolated pockets of ponded sediment along the eastern margin of the Tufts fan that have very low backscatter on the GLORIA sidescan images. The acoustic character of these pockets is similar to that of the late stage 2 turbidite deposits identified as the Missoula flood sequence in the Escanaba Trough (Zuffa et al. 2000). Where the airgun and 3.5-kHz seismic reflection profiles cross an isolated pocket of sediment characterized by widely spaced, parallel reflections (figs. 6*C*, 8*B*; fig. 9*A*, 9*B*), the backscatter image shows the lowest strength (*black*) returns (fig. 7). In all cases, these deeper, local basin fills are separated from the Tufts fan by one or more ridges (e.g., figs. 6*C*, 8*B*). These local basins are probably the deposits stripped from the upper part of flows that overtopped the ridge

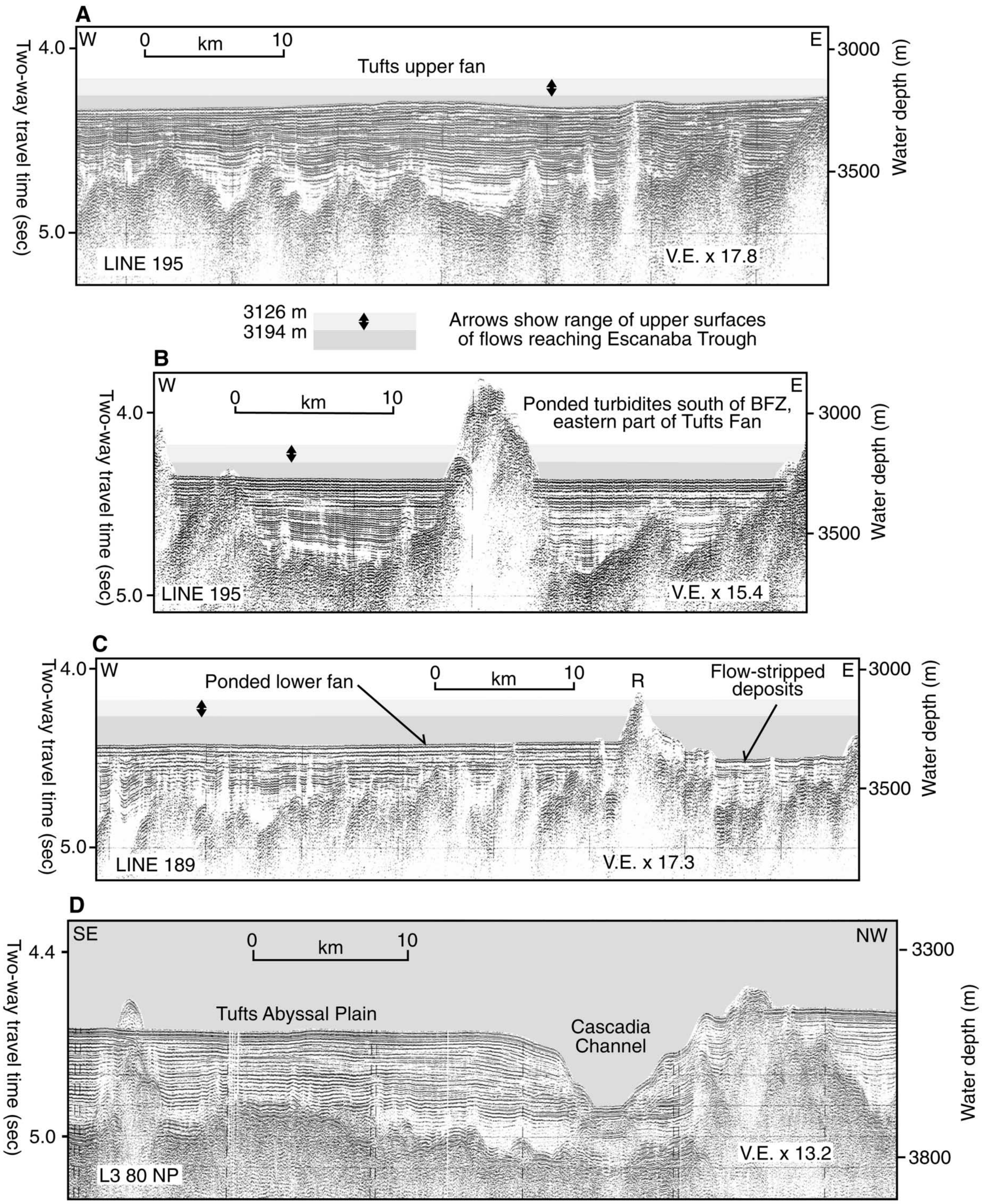


Figure 6. Single-channel, airgun seismic reflection profiles of the Tufts fan and the Cascadia Channel showing the projected tops of the turbidity currents that reached the Escanaba Trough. See figures 4 and 7 for location.

Table 2. Locations of Cores with Evidence for Latest Pleistocene Flood Deposits

Map ID	Original ID	Latitude	Longitude	Water depth (m)
C1[a]	6509–21A	44.058	129.937	3232
C2[a]	6509–25A	43.583	129.200	3334
C3[b]	6604–1	43.567	128.742	3329
C4[c]	6604–3	43.452	128.185	3180
C5[a]	6609–13	43.120	127.740	3266
C6[d]	W8809A–29GC	41.803	129.005	3288
C7[e]	W8809A–31GC	41.678	130.007	3136
C8[e]	W8809A–57GC	41.583	130.617	3330

[a] Duncan et al. 1970.
[b] Griggs et al. 1970.
[c] Duncan 1968.
[d] Dowsett and Poore 1999.
[e] Ortiz et al. 1997.

crests while the main flow continued to the south between the ridges. The GLORIA backscatter image shows brighter returns of linear ridge crests separating the low backscatter patches from the Tufts fan. Further, in all 3.5-kHz profiles that cross an isolated pocket of very low backscattered energy on the GLORIA image, the water depth is deeper than on the adjacent part of the Tufts fan (e.g., fig. 8*B*).

The lower area of the Tufts fan shows typical turbidite character in 3.5-kHz profiles with relatively high amplitude and continuous to discontinuous, subparallel reflectors (fig. 8*B*). This reflection character, common to much of the Tufts fan, is distinctly different from that of the isolated, local
q4 basin fills described previously (cf. fig. 8*B*, *left side*, with fig. 8*B*, *right side*, fig. 9*A*, 9*B*). This difference in reflection character results from "normal" turbidity current deposition on the fan surface where the coarser grains tend to be deposited during the passage of a turbidity current. In contrast, in the isolated pockets east of the fan proper as well as in the Escanaba Trough, the turbidity currents are trapped and deposit all sediment in the flow, resulting in relatively thick beds.

Only a few sediment cores are known from the general Tufts fan area. Core C4 (table 2; fig. 4), near the northeast corner of the fan at water depths of 3184 m, recovered nearly 3 m of Late Pleistocene sediment with a terrigenous component (Duncan 1968). Adjacent to the lower fan area, at a 3136-m depth, core C7 (table 2; fig. 4) recovered silty clay sediment; ^{14}C dates at 5–6-cm depths and 12–13-cm depths in the core were 15.38 Ka and 15.82 Ka, respectively (Ortiz et al. 1997). Core C6 (table 2; fig. 4) has a near-surface layer that dates to about 15.5 Ka (using the raw age from Dowsett and Poore [1999] and assuming a correction for the mixture of benthic and planktic forams they used for the ^{14}C age). Farther west, core C8 (table 2; fig. 4) at a 3330-m water depth recovered sediment dated at 14.9 and 15.0 Ka at core depths of 14–15 cm and 20–21 cm, respectively (Ortiz et al. 1997). These dated intervals overlie terrigenous sediment between a 172-cm and 257-cm depth in the core.

These cores confirm that terrigenous sediment has been deposited on the flank of Gorda Ridge (both within the fan area and to the west) between the lobe area of the fan and the thick ponded sequence at the base of the MFZ. The age of the upper parts of these cores is late stage 2 as in the Escanaba Trough, and the water depth falls within the range observed for deposition in the Escanaba Trough.

Where the Tufts fan impinges upon the high relief of the MFZ, >500 m of mostly turbidite sediment fills a trough just north of the ridge (Reid and Normark, in press). Thick sediment fill between the south end of the high ridges on the west flank of the Gorda Ridge and the MFZ continues eastward to the edge of Escanaba Trough (fig. 10*A*). Turbidity currents can enter the Escanaba Trough only through a fairly narrow gap between the Gorda Ridge and the MFZ (figs. 4, 11). The sill depth at this passage is currently about 3250 m (just south of the line of profile 10A). Onlap of reflectors from the west indicates that this sill has, at times, acted as a dam for currents moving across Tufts fan to the east along the MFZ. The sediment from the lower part of these currents is trapped on the western side of the sill (fig. 10*A*, *left side*) as is sediment from all thinner flows that might have reached the MFZ from the Cascadia Channel.

Zuffa et al. (2000) argued that the turbidite fill of the Escanaba Trough could not have come from the east. Their evidence was the blockage of the Astoria Channel documented by Goldfinger et al. (2000) and Wolf et al. (1999). Figure 10*A* and 10*B* shows that the turbidite fill of the Escanaba Trough wedges out to the east against the southern end of one of the high mountains of Gorda Ridge. The only other available 3.5-kHz profile (fig. 10*C*) also shows that the late stage 2 sediment of the Escanaba Trough (reflector sequence B through I) terminates along the eastern margin of the Escanaba Trough. Thus, the Missoula Flood deposits in the Escanaba Trough were deposited from flows that crossed the Tufts fan, were blocked by the relief of the MFZ, and then flowed eastward until intercepted by the deep rift valley of the Escanaba Trough.

Discussion

The turbidite fill of the Escanaba Trough provides only a partial record of the fate of the latest Pleis-

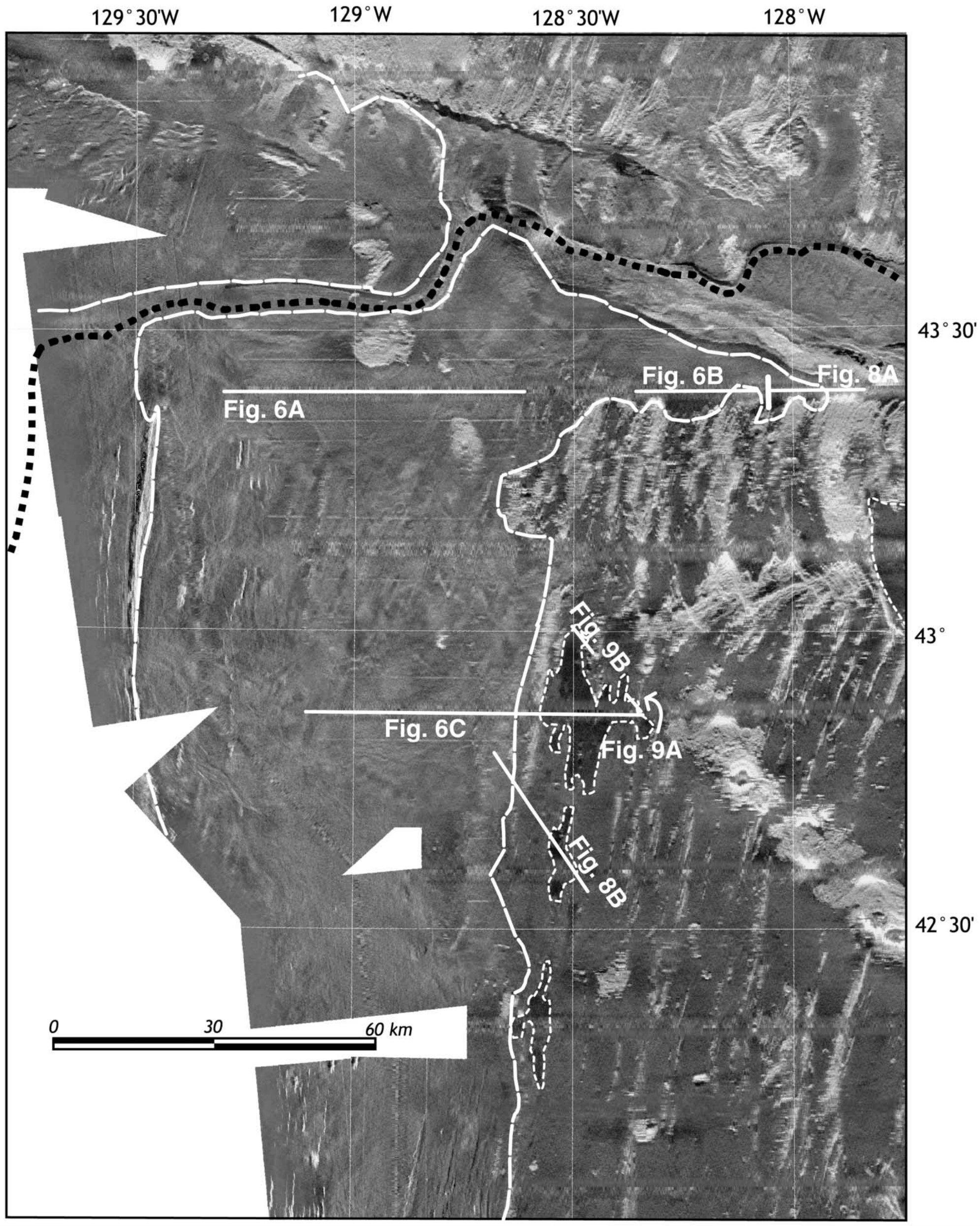


Figure 7. GLORIA (Geological LOng-Range Inclined ASDIC) sidescan sonar backscatter image of the northern Tufts fan (*white line south of the Cascadia Channel*). Turbidity-current deposits trapped in small basins shown as very low (*black*) backscatter along the eastern margin of the Tufts fan (see dotted white polygons close to long 128.5°30′W). Location of airgun and 3.5-kHz seismic reflection profiles of figures 6, 8, and 9 are shown. See figure 2 for location of image.

tocene glacial floods. Continuous coring at ODP site 1037 is limited to the last 55 Ka, but there is a clear correlation between the recovered sediment sequence and the seismic reflection profiles (both high-resolution 3.5-kHz data and deeper penetration airgun profiles; figs. 2, 3) that allows us to recognize the distinct acoustic character of the deposits, especially the late stage 2 beds, on the Tufts fan (figs. 8, 9).

The available age control on deposition at site 1037 suggests that thick sandy turbidite beds did not become common until about 18–20 Ka (fig. 3; Brunner et al. 1999). This change to thicker and coarser beds is probably not simply an indication

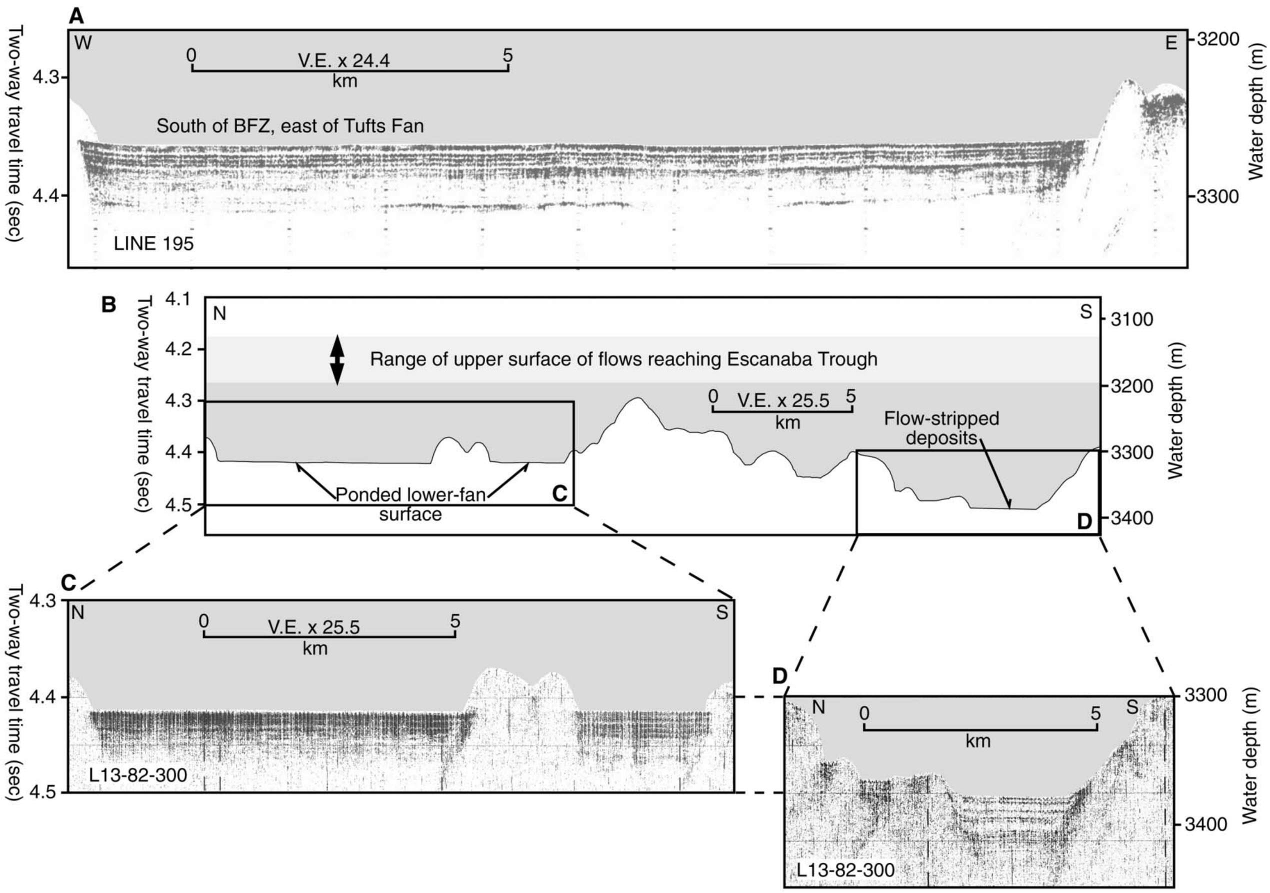


Figure 8. High-resolution 3.5-kHz profiles showing ponding of the youngest turbidite deposits. See figures 4 and 7 for location.

of larger floods reaching the ocean but rather that the pathway to the Escanaba Trough (Tufts fan) became more established. It is likely that the Tufts fan area received overbank as well as flow-stripped sediment at least periodically throughout much of the Late Pleistocene.

Whether sediment can reach the Pacific plate through the Cascadia Channel is a function of the nature of tectonic activity in the BFZ and the amount of sediment deposited on the Juan de Fuca plate (also called the Cascadia Basin). Both faulting and volcanism in the BFZ could result in periodic blockage of the Cascadia Channel. Even when the channel has a clear passage through the BFZ, there must be sufficient sediment brought to the Juan de Fuca plate so that the fracture zone topography does not block turbidity current flows. It is likely that sediment accretion as a result of subduction along the Cascadia margin during times of low (=normal?) sediment input might sufficiently reduce the sediment on the Juan de Fuca plate so that little was available to escape to the Pacific plate.

Volumetric Estimates of Probable Lake Missoula Flood Deposits on the Sea Floor. There are sufficient data to do a rough estimate of the amount of sediment deposited on the Juan de Fuca plate and Pacific plate during late isotope stage 2. First, we estimate the total volume of turbidite sediment on the Pacific plate and evaluate how much of it might be related to late stage 2 flooding (i.e., deposits younger than 16 Ka that are equivalent in age to the Lake Missoula floods). Only the major geographic areas are considered: Escanaba Trough, Tufts fan (including adjacent areas of flow-stripped sediment), Tufts Abyssal Plain, Cascadia Channel, and Astoria Fan.

Escanaba Trough. Late stage 2 deposits in the Escanaba Trough are 120 m thick at ODP site 1037 (Shipboard Scientific Party 1998; Zuffa et al. 2000). The base of the sequence can be recognized on seis-

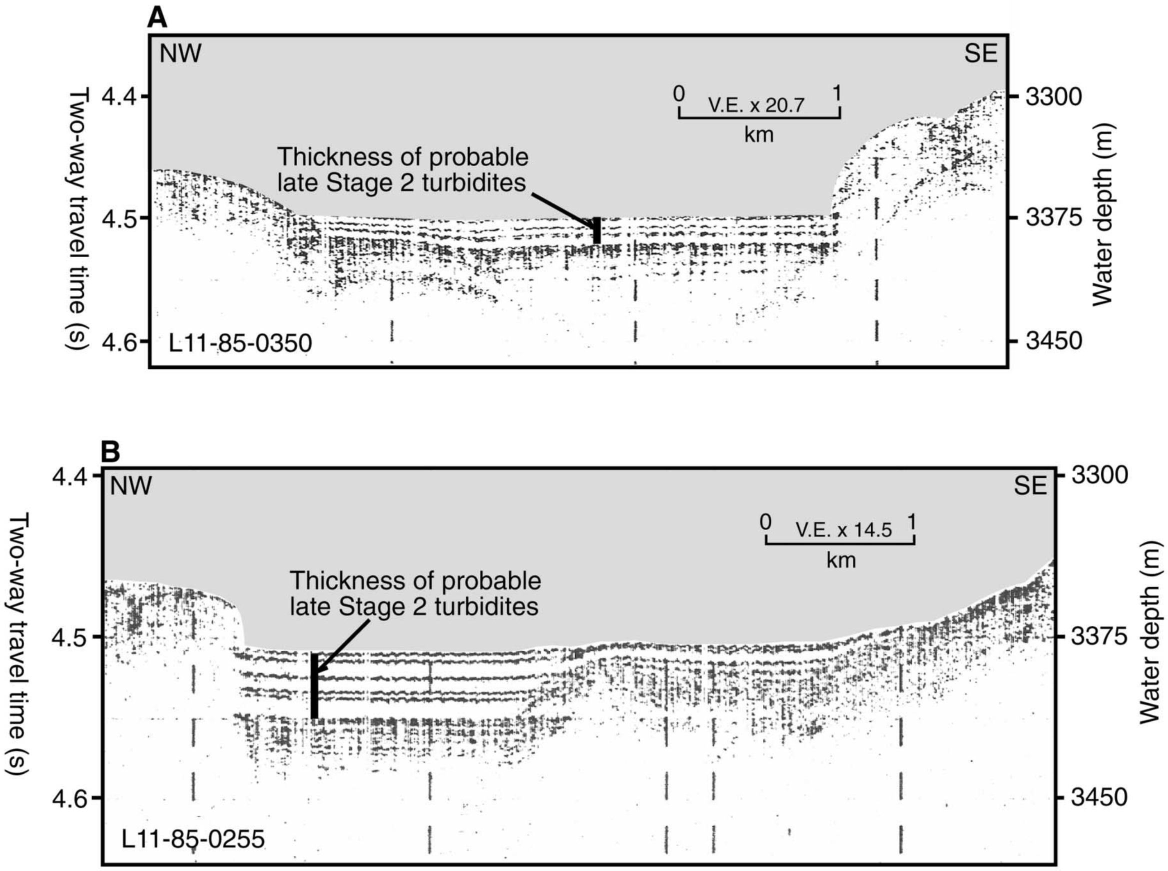


Figure 9. High-resolution 3.5-kHz profiles showing isolated areas of ponded, flow-stripped (probable late stage 2) turbidites with a character similar to that seen in the Escanaba Trough. See figures 4 and 7 for location.

mic reflection profiles between ODP site 1037 and DSDP site 35, where it is slightly less than 110 mbsf (see fig. 3.3 in Davis and Becker 1994). The volume of late stage 2 deposits in the Escanaba Trough is about 115 km^3 (less than the volume originally es-
q5 timated by Zuffa et al. 2000; table 3); our new estimate uses a revised measurement (1.1×10^3 km^2) of the area over which the sequence is found. Similarly, our estimate of the volume of the deposit related to the initial outburst from Lake Missoula (*M1*, fig. 3) is revised downward from 84 km^3 (the lower part of unit B in Zuffa et al. 2000) to 55 km^3, which is still nearly half of the total Lake Missoula deposits. Seismic reflection data provide an estimate of 465 km^3 for the total volume of latest Pleistocene (i.e., from ~55 ka to the base of the Holocene) turbidite sediment in the Escanaba Trough, with late stage 2 (*M1* + *M2*, fig. 3) comprising about 25% of the total fill.

Tufts Fan. The seismic reflection data can be used for a rough estimate of the volume of sediment that formed the Tufts fan (see also Reid and Normark, in press). Flat-lying reflectors, where local low relief (e.g., autocyclic relief on the fan surface) has been buried, form the basis for identifying latest Pleistocene deposits. The reflector spacing of the latest Pleistocene flood deposits on the Tufts fan is less than in the Escanaba Trough because the turbidity currents were trapped in the dead-end rift valley. On the Tufts fan, only some sediment was deposited as the turbidity currents transited the fan area.

Using the area of the fan between the Cascadia Channel and the Escanaba Trough (~ 2×10^4 km^2), the volume of latest Pleistocene deposits is estimated to be about 600 km^3, including 20 km^3 in the basins north of the fan apex that received flow-stripped sediment. The latest Pleistocene deposits represent about 15% of the total. Our estimates suggest that the late stage 2 sequence (M1 + M2 equivalent) is 315 km^3 or about half the volume of all the latest Pleistocene deposits.

Tufts Abyssal Plain. The Tufts fan represents a relatively small turbidite deposit compared with

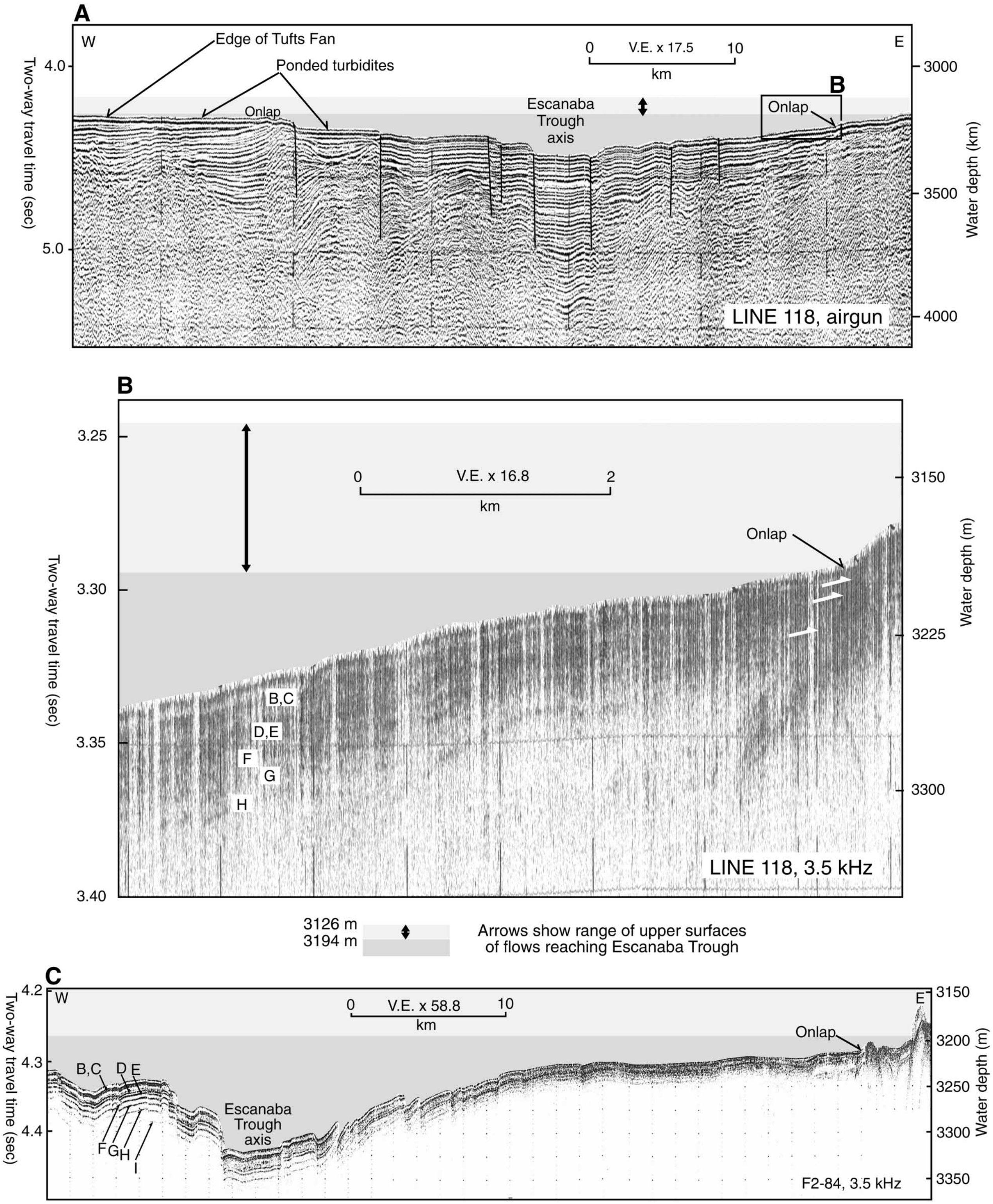


Figure 10. Airgun seismic reflection profile (*A*) and 3.5-kHz high-resolution profiles (*B*, *C*) across the mouth of the Escanaba Trough (subparallel to the Mendocino Fracture Zone) showing the eastward wedging out of the latest Pleistocene turbidite deposits. See figure 4 for location.

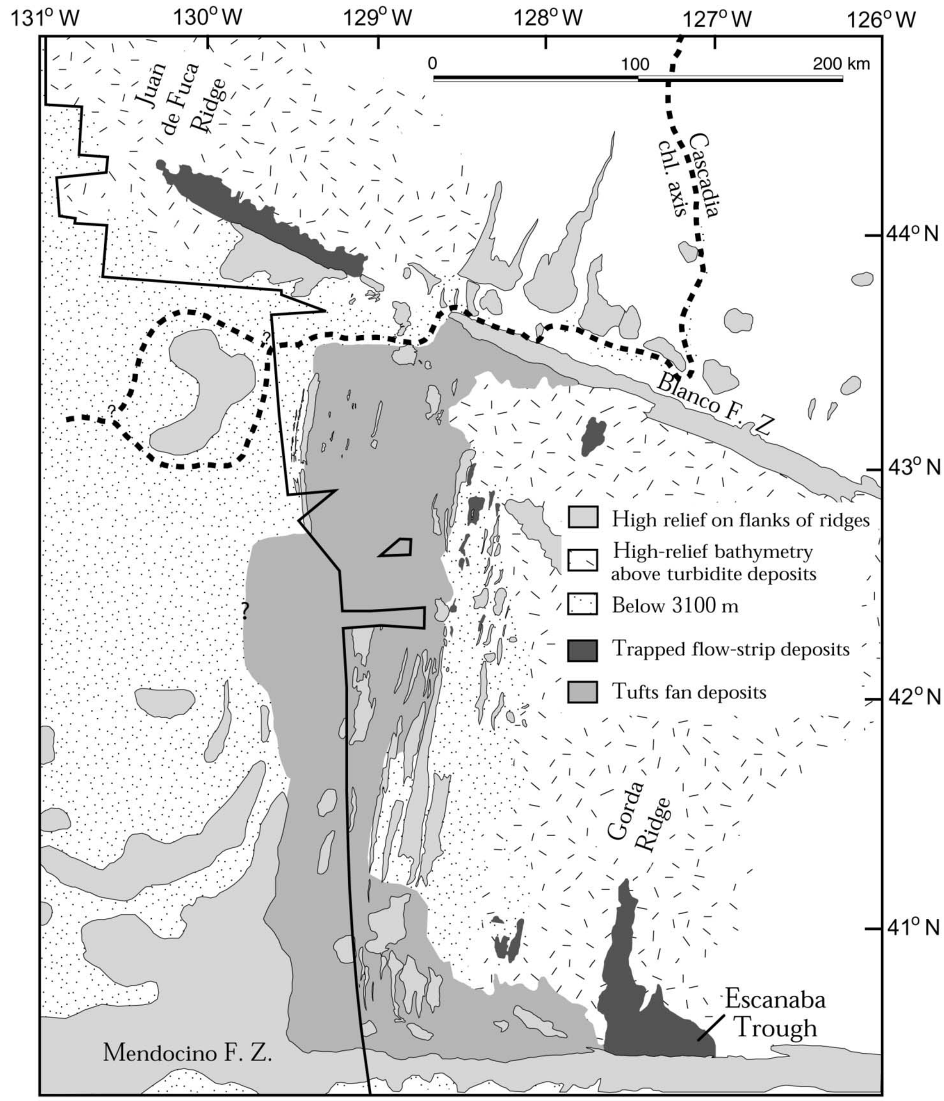


Figure 11. Schematic map of the Tufts fan and areas of flow-stripped and trapped turbidite sediment on the west flank of Gorda Ridge.

the area of the Tufts Abyssal Plain (fig. 12). The relief of the Cascadia Channel throughout the area of overbank flow, which is the source for the Tufts fan, is generally 200–300 m. A significant portion of the sediment moving along the channel continued flowing west; the cross-sectional area of the channel west of the Tufts fan is the largest within the study area (fig. 4*D*). A significant part of the larger turbidity currents from all latest Pleistocene floods must have continued westward to be deposited on the Tufts Abyssal Plain.

The margins of and local relief on the Tufts Abyssal Plain are not well known because of a scarcity of data. Using the information from Hurley (1960) and Stevenson and Embley (1987), it appears that the area of the Tufts Abyssal Plain is probably more than 3×10^5 km^2. The area upstream from the confluence of the Horizon and Mukluk channels (fig. 12) is about 2.75×10^5 km^2. There are far fewer data to determine the volume of turbidites on the Tufts Abyssal Plain than on the Tufts fan, but it is instructive to evaluate what is known. Winterer (1989) compiled a map of sediment thickness in the North Pacific Ocean. His contours show that the accumulated sediment locally exceeds 0.4 km in several places within the general area of the Tufts Abyssal Plain (fig. 12). The nonturbiditic (pelagic) sediment is probably only 25% of this thickness

Table 3. Volume of Sediment (km^3) from the Late Stage 2 Flood Outbursts

Depositional geographic area	Late stage 2 floods	Latest Pleistocene floods	Estimated total turbidite deposits
Escanaba Trough	115	465	465
Tufts fan	315	605	3900
Tufts Abyssal Plain	~470	4700	47,000
Astoria Fan	550	2074	19,000
Totals	1450	7879	70,735

(based on the 0.1-km contours of Winterer [1989] and on the observed thickness of transparent [assumed pelagic] sediment that underlies the turbidite sequence in seismic reflection profiles; e.g., fig. 6*D*). Figure 12 also shows cores that have a terrigenous sediment component (Moore 1989; see also National Geophysical Data Center web site http://www.ngdc.noaa.gov/mgg/image/2minrelief.html). The shaded relief view of the northeast Pacific based on satellite gravity data (Smith and Sandwell 1997) indicates the area of smoothing of sea-floor relief in the vicinity of the Tufts Abyssal Plain that was used to approximate the limits of the Tufts Abyssal Plain as shown in figure 12.

Use of isopach data alone suggests that a minimum of 4.7×10^4 km^3 of turbidite sediment may constitute the Tufts Abyssal Plain. This estimate represents a conservative interpretation in that only average-thickness or minimum-thickness values were used. For example, in the area between the 0.2- and 0.4-km isopachs from Winterer (1989), we used the average (0.3 km) and then corrected for the thickness of the pelagic layer (−0.1 km); therefore, we assumed only a 0.2-km thickness for the entire area between these isopachs. A similar assumption was used for the >0.4-km isopach. In addition, the estimate considers only the area of the plain fed by the Cascadia Channel (i.e., upslope from its confluence with the Horizon and Mukluk Channels; Stevenson and Embley 1987). Turbidity currents from the Cascadia Channel could have kept moving and deposited sediment for several hundred more kilometers to the west.

If the latest Pleistocene floods deposited 10% of the total volume calculated for the Tufts Abyssal Plain, the total sediment volume on the Pacific plate from the latest Pleistocene flood episodes is >5000 km^3 (4700 km^3 from the Tufts Abyssal Plain plus the 1070 km^3 on the Tufts fan and in the Escanaba Trough; table 3). We believe that 10% is an appropriate value, given that the observed ratio of late stage 2 deposits to latest Pleistocene deposits on the Tufts fan is about 15%. Even assuming that only 1% of the Tufts Abyssal Plain sediment comes from late stage 2 events, the resulting volume is 470 km^3, which is itself more than the combined sum for the Tufts fan and the Escanaba Trough (table 3).

Astoria Fan. Published seismic reflection data for the Astoria Fan do not indicate any clear seismic stratigraphic horizon that might be correlated with the base of the latest Pleistocene flood sequence. An approximation of the volume of sediment that might have resulted from the floods is available from DSDP site 174 from the middle part of the Astoria Fan (fig. 1; Shipboard Scientific Party 1973). Reevaluation of the micropaleontologic record from site 174 suggests that isotope stage 5e (120 Ka) is at 125 mbsf (J. Barron, written communication, June 18, 2002). The average sedimentation rate from stage 5e to the present is then 1.04 m/10^3 yr. Thus, the base of the latest Pleistocene flood sequence would be about 57 mbsf. Nelson et al. (1988) give a Holocene sedimentation rate of 0.08 m/10^3 yr for the fan surface outside of channels. A conservative estimate is that the latest Pleistocene flood sequence is about 56 m thick on the Astoria midfan area. Assuming that the midfan area provides an approximation of the average thickness for the Astoria Fan deposits, then nearly 2100 km^3 of flood sediment was deposited on the fan during the latest Pleistocene. The same assumptions for the late stage 2 deposits yield a volume of 550 km^3. Because we are using the average sedimentation rate for 120 Ka, it is highly likely that our estimate of the late stage 2 flood sequence on the Astoria Fan is conservative.

Cascadia Channel. As the main conduit for sediment from the Columbia River to the Pacific plate, it is reasonable that some latest Pleistocene deposits should remain in and near the channel. As noted previously, there is evidence for flood sediment in the floor of the channel, but neither existing core data nor high-resolution seismic reflection data define the thickness of the deposits. Available profiles suggest that the Cascadia Channel in the BFZ alone may contain 350 km^3 of turbidites; even if 10% of these were from the latest Pleistocene flood events, the additional 35 km^3 is a minor amount.

The right-hand channel margin of the Cascadia Channel upstream of the BFZ shows clear evidence of ponding of the most recent sediment similar to that observed in the deeper-penetration seismic reflection data (see fig. 4*A* in Reid and Normark, in press). Thus, the totals for flood-related sediment in table 3 probably are larger than stated.

Implications from Late Stage 2 (Missoula Flood) De-

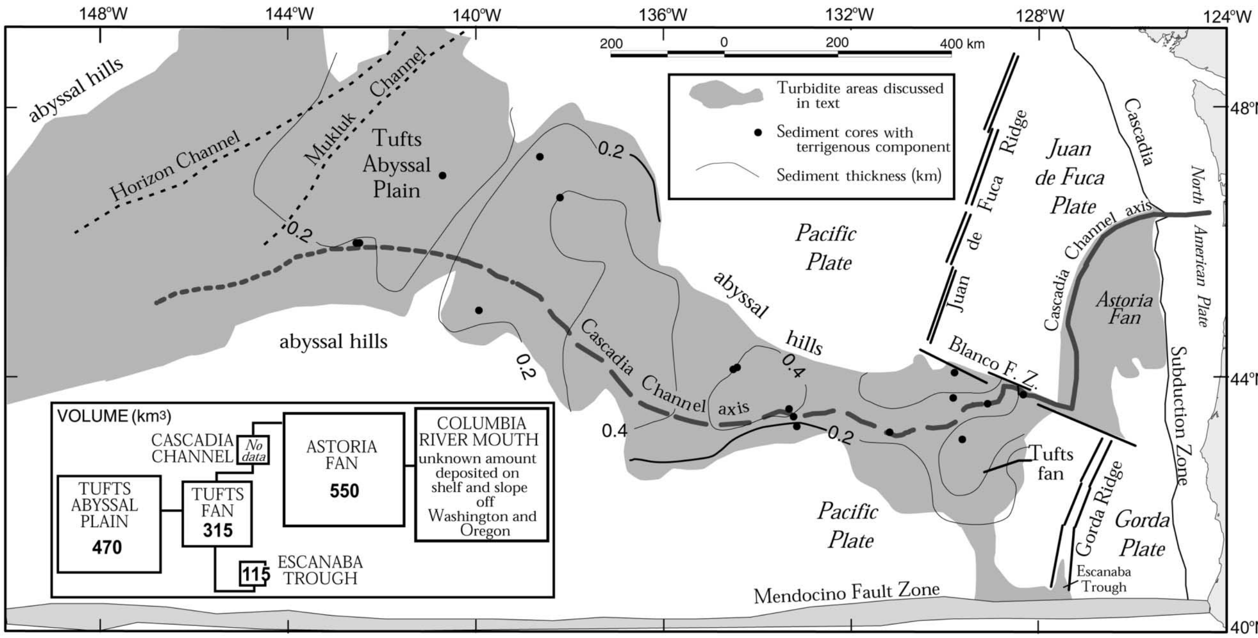


Figure 12. Schematic map of the eastern Pacific Ocean shows the probable extent of the Tufts Abyssal Plain, which is fed by the Cascadia Channel (*dashed line where poorly known*); map is based on Hurley (1964) and modified using ETOPO2 interpretation of sea-floor relief (Smith and Sandwell 1997). The 0.2-km and 0.4-km sediment isopachs, which probably reflect turbidite deposits, from Winterer (1989) are shown for reference. Positions of the Horizon and Mukluk Channels are taken from Stevenson and Embley (1987). *Inset*, Flow diagram shows sediment volumes for the initial (15.5 Ka) outburst from glacial Lake Missoula. See table 3 and text for explanation.

posits. The thickest turbidite bed cored in the Escanaba Trough was deposited at about 15.5 Ka and underlies a section of thick pre-Holocene sand beds. Karlin and Lyle (1986) and Normark et al. (1994) showed that Holocene sediment thickness is generally <2 m throughout the Escanaba Trough and includes only thin turbidite beds of only local extent and origin. The sandy section above 120 mbsf at site 1037 (fig. 3) corresponds in age to the late Wisconsinan floods from glacial Lake Missoula (e.g., after 16 Ka; Baker and Bunker 1985). O'Conner and Baker (1992) evaluated the evidence for peak discharge from Lake Missoula, which they note was consistent with an early cataclysmic discharge preceding multiple subglacial jökulhlaups. The seismic reflection and core data provide strong arguments to show that the early cataclysmic discharge reached the Escanaba Trough.

The estimated volume of sediment carried to the ocean by the late stage 2 flood outbursts is a minimum of 1450 km^3. The total could be substantially higher if deposits of this age exceed 1% of the total sediment on the Tufts Abyssal Plain, as was assumed for table 3. Using the proportion of the first bed to total thickness of the presumed Lake Missoula deposits in the Escanaba Trough (i.e., nearly 1 : 1; fig. 3), the largest outburst (just after 16 Ka) might have transported about 700 km^3. This estimate does not include any contribution of sediment left along the Cascadia Channel or its western levee north of the BFZ for the channel reach between the base of the continental slope and the head of the Tufts fan (fig. 1). For these reasons, we think that 700 km^3 is a reasonable order-of-magnitude volume estimate for sediment carried to the ocean during the largest late stage 2 event, the cataclysmic initial outburst from glacial Lake Missoula.

Onland evidence for maximum water discharge from glacial Lake Missoula suggests 17×10^6 m^3 s^{-1} near the point of release and 10×10^6 m^3 s^{-1} downstream of the Channeled Scablands (O'Conner and Baker 1992). Estimates of the peak sediment discharge from the largest outburst from Lake Missoula suggest that as much as 1000 km^3 of sediment was delivered to the ocean (J. Milliman, written communication, May 2002). This estimate agrees well with our estimated minimum volume for sediment carried to the ocean (table 3).

The volume of latest Pleistocene sediment on the

Pacific plate is on the order of 10% of the total turbidite sediment brought to the Pacific plate through the BFZ. Thus, it appears that sediment from the Pacific Northwest might have reached the Pacific plate through the Cascadia Channel during much of the Pleistocene if not a longer interval (e.g., McDonald and Busacca 1988; Bjornstad et al. 2001; Pluhar et al. 2002). Sediment transport through the BFZ has probably not been continuous throughout the Pleistocene but rather was limited to intervals where sediment is deposited on the Juan de Fuca plate sufficient to fill the Cascadia Basin and allow outflow to the west or south. For example, drilling at DSDP site 174 on the distal part of the Astoria Fan showed that 284 m of Late Pleistocene turbidites overlie Pleistocene/Pliocene pelagic mud and thin bedded turbidites. The important point is that sediment input can fill the Cascadia Basin to its brim only periodically, perhaps only during glacial periods.

Conclusions

The astounding effects of the catastrophic floods from glacial Lake Missoula and other Late Pleistocene sources are not confined to the subaerial environment in Washington, Idaho, and Oregon. Reaching the ocean, the flood-transported sediment continued moving downslope as hyperpycnal flows. These flows overwhelmed the main conduit for the flows, the Cascadia Channel, building the Tufts fan as a result of overflow on the south side of the channel upon reaching the Pacific plate. The largest of these turbidity current overflows reached the Escanaba Trough, where they were trapped and have provided a well-documented record of the flood events at ODP site 1037 (Zuffa et al. 2000). The volume of the sediment carried to the ocean by floods during late isotope stage 2 is on the order of 1500 km^3 (table 3). The largest outburst at 15.5 Ka alone may have transported nearly half of that sediment.

These deposits, however, constitute only a small portion of the terrigenous sediment deposited on the Pacific plate that moved across the oceanic ridge system, probably through the BFZ, during the Pleistocene. A much larger volume of turbidites that underlies the late stage 2 flood sequence is derived from a long history of pre-Wisconsinan flood events that occurred periodically throughout the Pleistocene or longer.

ACKNOWLEDGMENTS

We thank J. D. Milliman and K. L. Farnsworth for stimulating discussions to place the magnitude of the glacial Lake Missoula marine deposits in a global perspective. C. Degnan assisted with data retrieval for our map figures and J. Barron clarified interpretation of ages from existing non-USGS core samples. The article has benefited from reviews by P. R. Carlson, J. D. Milliman, F. Serra, V. R. Baker, and B. N. Bjornstad.

REFERENCES CITED

Atwater, B. 1986. Pleistocene glacial-lake deposits of the Sanpoil River Valley, northeastern Washington. U.S. Geol. Surv. Bull. 1661.

Baker, V. R. 1973. Paleohydrology and sedimentology of Lake Missoula flooding in eastern Washington. Boulder, Colo., Geol. Soc. Am. Spec. Pap. 144, 79 p.

Baker, V. R.; Bjornstad, B. N.; Busacca, A. J.; Fecht, K. R.; Kiver, E. P.; Moody, U. L.; Rigby, J. G.; Stradling, D. F.; and Tallman, A. M. 1991. Quaternary geology of the Columbia Plateau. *In* Morrison, R. B., ed. Quaternary nonglacial geology. Conterminus U.S. geology of North America. Boulder, Colo., Geol. Soc. Am. K-2, p. 215–250.

Baker, V. R., and Bunker, R. C. 1985. Cataclysmic Late Pleistocene flooding from glacial Lake Missoula: a review. Quat. Sci. Rev. 4:1–41.

Bjornstad, B. N.; Fecht, K. R.; and Pluhar, C. J. 2001. Long history of pre-Wisconsin, ice age cataclysmic floods: evidence from southeastern Washington State. J. Geol. 109:695–713.

Bretz, J. H.; Smith, H. T. U.; and Neff, G. E. 1956. Channelized scabland of eastern Washington: new data and interpretations. Geol. Soc. Am. Bull. 67:957–1049.

Brunner, C. A.; Normark, W. R.; Zuffa, G. G.; and Serra, F. 1999. Deep-sea sedimentary record of the late Wisconsin cataclysmic floods from the Columbia River. Geology 27:463–466.

Clague, J. J.; Barendregt, R.; Enkin, R. J.; and Foit, F. F., Jr. 2003. Paleomagnetic and tephra evidence for tens of Missoula floods in southern Washington. Geology 31:247–250.

Davis, E. E., and Becker, K. 1994. Thermal and tectonic structure of Escanaba Trough: new heat-flow measurements and seismic-reflection profiles. *In* Morton, J. L.; Zierenberg, R. A.; and Reiss, C. A., eds. Geologic, hydrothermal, and biologic studies at Escanaba Trough, Gorda Ridge, offshore northern California. U.S. Geol. Surv. Bull. 2022, p. 45–64.

DeCharon, A. V. 1986. Structure and tectonics of Cascadia segment, central Blanco Transform Fault Zone. M.S. thesis, Oregon State University, Corvallis. q6

Dowsett, H. J., and Poore, R. Z. 1999. Last interglacial sea-surface temperature estimates from the California margin: improvements to the Modern Analog Technique. U.S. Geol. Surv. Bull. 2171, 12 p.

Duncan, J. R., Jr. 1968. Late Pleistocene and postglacial sedimentation and stratigraphy of deep-sea environments off Oregon. Ph.D. thesis, Oregon State University, Corvallis.

Duncan, J. R.; Fowler, G. A.; and Kulm, L. D. 1970. Planktonic foraminifera-readiolarian ratios and Holocene-late Pleistocene deep sea stratigraphy off Oregon. Geol. Soc. Am. Bull. 81:561–566.

q7 Duncan, J. R., and Kulm, L. D. 1970. Mineralogy, provenance and dispersal history of Late Quaternary deep-sea sands in Cascadia Basin and Blanco Fracture Zone off Oregon. J. Sediment. Petrol. 40:874–887.

q8 EEZ-SCAN 84 Scientific Staff. 1986. Atlas of the exclusive economic zone, western coterminous United States. U.S. Geol. Surv. Misc. Invest. Series I-1792, 152 p., scale 1 : 500,000.

Embley, R. W. 1985. A locally formed deep ocean canyon system along the Blanco Transform, Northeast Pacific. Geo-Mar. Lett. 5:99–104.

Goldfinger, C.; Kulm, L. D.; McNeill, L. C.; and Watts, P. 2000. Super-scale failure of the southern Oregon Cascadia margin. Pure Appl. Geophys. 157:1189–1226.

Griggs, G. B., and Kulm, L. D. 1970*a*. Physiography of Cascadia deep-sea channel. Northwest Sci. 44:82–94.

———. 1970*b*. Sedimentation in Cascadia deep-sea channel. Geol. Soc. Am. Bull. 81:1361–1384.

———. 1973. Origin and development of Cascadia deep-sea channel. J. Geophys. Res. 78:6325–6339.

Griggs, G. B.; Kulm, L. D.; Waters, A. C.; and Fowler, G. A. 1970. Deep-sea gravel from Cascadia channel. J. Geol. 78:611–619.

q9 Grim, M. S.; Chase, T. E.; Evenden, G. I.; Holmes, M. C.; Normark, W. R.; Wilde, P.; Fox, C. G.; Lief, C. J.; and Seekins, B. A. 1992. Map showing bottom topography of the Pacific continental margin. Strait of Juan de Fuca to Cape Mendocino. U.S. Geol. Surv. Misc. Invest. Ser. Map I-2091-C.

Hurley, R. J. 1960. The geomorphology of abyssal plains in the northeast Pacific Ocean. Scripps Inst. Oceanog. SIO Ref. 60–7, 105 p.

———. 1964. Analysis of flow in Cascadia deep-sea channel. *In* Miller, R. L., ed. Papers in marine geology: Shepard commemorative volume. New York, Macmillan, p. 117–132.

Karlin, R., and Lyle, M. 1986. Sediment studies on the Gorda Ridge. Oregon Dept. of Geol. Min. Ind. Open-File Rep. 0-86-19, 76 p.

Martinson, D. G.; Pisias, N. G.; Hays, J. D.; Imbrie, J.; Moore, T. C., Jr.; and Shackleton, N. J. 1987. Age dating and the orbital theory of the ice ages: development of a high-resolution 0 to 300,000-year chronostratigraphy. Quat. Res. 27:1–29.

McDonald, E. V., and Busacca, A. J. 1988. Record of pre–late Wisconsin giant floods in the Channeled Scabland interpreted from loess deposits. Geology 16:728–731.

Moore, C. J. 1989. Surface-sediment composition of the Northeast Pacific plate 2B. *In* Winterer, E. L.; Hussong, D. M.; and Decker, R. W., eds. The Eastern Pacific Ocean and Hawaii (Geology of North America, Vol. N). Boulder, Colo., Geol. Soc. Am., 1 sheet.

Mulder, T., and Syvitski, J.P.M. 1995. Turbidity currents generated at mouths of rivers during exceptional discharges to the world oceans. J. Geol. 103:285–299.

Nelson, C. H. 1985. Astoria Fan, Pacific Ocean. *In* Bouma, A. H.; Normark, W. R.; and Barnes, N. E., eds. Submarine fans and related turbidite systems. New York, Springer, p. 45–50. q10

Nelson, C. H.; Kulm, L. D.; and Carlson, P. R. 1988. The Mount Mazama climatic eruption (6.900 yrs B.P.) and resulting convulsive sedimentation on the Crater Lake caldera floor, continent and ocean basins. Boulder, Colo., Geol. Soc. Am. Spec. Pap. 229, p. 37–57.

Normark, W. R.; Gutmacher, C. E.; Zierenberg, R. A.; Wong, F. L.; and Rosenbauer, R. J. 1994. Sediment fill of Escanaba Trough. *In* Morton, J. L.; Zierenberg, R. A.; and Reiss, C. A., eds. Geologic, hydrothermal, and biologic studies at Escanaba Trough, Gorda Ridge, offshore northern California. U.S. Geol. Surv. Bull. 2022, p. 91–129.

Normark, W. R.; Piper, D. J. W.; Posamentier, H.; Pirmez, C.; and Migeon, S. 2002. Variability in form and growth of sediment waves on turbidite channel levees. Mar. Geol. 192:23–58.

Normark, W. R.; Reid, J. A.; Klitgord, K. D.; Ross, S. L.; and Zierenberg, R. A. 1997. Tectonism and turbidites in Escanaba Trough, southern Gorda Ridge. EOS Trans. Am. Geophys. Union 78:F630.

Normark, W. R., and Serra, F. 2001. Vertical tectonics in northern Escanaba Trough as recorded by thick Late Quaternary turbidites. J. Geophys. Res. 106:13,793–13,802.

O'Conner, J. E., and Baker, V. R. 1992. Magnitudes and implications of peak discharges from glacial Lake Missoula. Geol. Soc. Am. Bull. 104:267–279.

Ortiz, J.; Mix, A.; Hostetler, S.; and Kashgarian, M. 1997. The California Current of the last glacial maximum: reconstruction at 42°N based on multiple proxies. Paleoceanography 12:191–205.

Piper, D. J. W.; Hiscott, R. N.; and Normark, W. R. 1999. Outcrop-scale acoustic facies analysis and latest Quaternary development of Hueneme and Dume submarine fans, offshore California. Sedimentology 46: 47–78.

Piper, D. J. W., and Normark, W. R. 1983. Turbidite depositional patterns and flow characteristics, Navy submarine fan, California Borderland. Sedimentology 30: 681–694.

Pluhar, C. J.; Reidel, S.; Bjornstad, B.; Nelson, P. B.; and Coe, R. S. 2002. New magnetostratigraphic analysis indicates that onset of Pleistocene cataclysmic flooding predates 1.07 Ma in east-central Washington. Geol. Soc. Am. Abstr. Prog. (Cordilleran Sect.) 34(5), p. A-25.

Reid, J. A., and Normark, W. R. In press. Tufts Submarine fan: turbidite gateway to Escanaba Trough. U.S. Geol. q11

Surv. Bull. Available at http://pubs.usgs.gov/products/books/bulletins.html.

Shaw, J.; Munro-Stasiuk, M.; Sawyer, B., Beaney, C.; Lesemann, J.-E.; Musacchio, A.; Rains, B.; and Young, R. R. 1999. The channeled scabland: back to Bretz? Geology 27:605–608.

Shipboard Scientific Party. 1970. Site 35. *In* Kulm, L. D., von Huene, R. E., et al., eds. Initial reports of the Deep Sea Drilling Project 18. Washington, D.C., Government Printing Office, p. 97–167.

———. 1973. Site 174. *In* McManus, D. A.; Burns, R. E., et al., eds. Initial reports of the Deep Sea Drilling Project 5. Washington, D.C., Government Printing Office, p. 165–202.

q12 ———. 1998. Escanaba Trough: reference site (site 1037). *In* Fouquet, Y.; Zierenberg, R. A.; Miller, D. J.; et al., eds. Proc. Ocean Drilling Program initial reports 169. College Station, Tex., p. 205–252.

Smith, W. H. F., and Sandwell, D. T. 1997. Global sea floor topography from satellite altimetry and ship depth soundings. Science 277:1956–1962.

Stevenson, A. J., and Embley, R. W. 1987. Deep-sea fan bodies, terrigenous turbidite sedimentation, and petroleum geology, Gulf of Alaska. *In* Scholl, D. W.; Grantz, A.; and Vedder, J. G., eds. Geology and resource potential of the continental margin of western North America and adjacent ocean basins—Beaufort Sea to Baja California. Circum-Pacific Council Energy Min. Resour. Earth Sci. Ser. 6, p. 503–522.

Vallier, T. L. 1970. The mineralogy of some turbidite sands from sites 32 and 35. *In* McManus, D. A., et al., eds. Initial reports of the Deep Sea Drilling Project 5. Washington, D.C., Goverment Printing Office, p. 535–539.

Vallier, T. L.; Harold, P. J.; and Girdley, W. A. 1973. Provenances and dispersal patterns of turbidite sand in Escanaba Trough, northeastern Pacific Ocean. Mar. Geol. 15:67–87.

Waitt, R. B., Jr. 1980. About forty last-glacial Lake Missoula jökulhlaups through southern Washington. J. Geol. 88:653–679.

———. 1985. Case for periodic, colossal jökulhlaups from Pleistocene glacial Lake Missoula. Geol. Soc. Am. Bull. 96:1271–1286.

———. 1994. Scores of gigantic, successively smaller Lake Missoula floods through Channeled Scabland and Columbia Valley. *In* Swanson, D. A., and Haugerud, R. A., eds. Geologic field trips in the Pacific northwest. Boulder, Colo., Geol. Soc. Am. Annu. Mtg. 1K, 88 p.

Winterer, E. L. 1989. Sediment thickness map of the Northeast Pacific. *In* Winterer, E. L.; Hussong, D. M.; and Decker, R. W., eds. The Eastern Pacific Ocean and Hawaii: the geology of North America. Boulder, Colo., Geol. Soc. Am. N, p. 307–310.

Wolf, S.; Nelson, C. H.; and Hamer, M. 1999. Turbidite pathways on Cascadia Basin and Tufts Abyssal Plain. Pt. A. Astoria channel to Mendocino channel. U.S. Geol. Surv. Open File Rep. 99–157, 7 sheets.

Zuffa, G. G.; de Rosa, R.; and Normark, W. R. 1997. Shifting sources and transport paths for the Late Quaternary Escanaba Trough sediment fill (northeast Pacific). Riv. Geol. Sed. Geol. Mar. 59:35–53.

Zuffa, G. G.; Normark, W. R.; Serra, F.; and Brunner, C. A. 2000. Turbidite megabeds in an oceanic rift valley recording jokulhlaups of Late Pleistocene glacial lakes of the western United States. J. Geol. 108:253–274.

QUERIES TO THE AUTHOR

1 I changed "110 kya" to "110,000 yr ago" per our style. Is edit correct?

2 In table 1, will it be confusing to your readers that the note mentions bed I but there is no I in the table?

3 Can you break this long paragraph into two or more paragraphs, please?

4 Please check your citation of figures 8 and 9 here. I am not sure what is being compared with "fig. 8*B*, left side." Is it only fig. 8*B*, right side, or is it also fig. 9*A* and 9*B*?

5 In table 3 the totals don't add up. The first column is correct, but the other two columns are not. Please correct or explain discrepancy in a note.

6 For DeCharon 1986, is Corvallis the correct location of the university?

7 I could not find a citation for Duncan and Kulm 1970. Please let us know where citation should be inserted into text or this reference should be deleted from the reference list.

8 In EEZ-SCAN 84 you have "coterminous," and in Baker et al. you have "conterminous." Are both correct?

9 For Grim et al. 1992 (and the other maps in the references), please add the map's scale if you have it.

10 I could not find a citation for Nelson 1985. Please let us know where citation should be inserted into text.

11 Please supply any available update for Reid and Normark (in press). Also, I could not find this bulletin listed at the web site you provided. Please check. When will it be posted?

12 For Shipboard Scientific Party 1998, please provide publisher if available.

The Journal of Geology

Hinds Geophysical Laboratory
5734 South Ellis Avenue
Chicago, IL 60637 USA

Reprint Order Form

Please return this form even if no extra reprints are ordered. NOTE: 50 reprints without covers are provided at no charge if page charges are contributed.

( ) NO EXTRA REPRINTS DESIRED

AUTHORS: REPRINT ORDER MUST BE RECEIVED PRIOR TO PRINTING OF JOURNAL ISSUE. Please return this form immediately <u>even if no reprints are desired</u>. Reprints ordered through an institution will not be processed without a purchase order number. Payment by check, Money Order, Visa, or MasterCard is required with all orders not accompanied by an institutional purchase order or purchase order number. **Make checks and purchase orders payable to The University of Chicago Press.**

TO BE COMPLETED BY AUTHOR:

The Journal of Geology Vol ______ No _____ Month ____________________ Page numbers ________________________

Author(s): ____ No of pages in article __________

Title of Article: ____

REPRINT PRICE LIST: Prices include shipping for U.S. and Canadian orders. Non-U.S and non-Canadian orders are shipped via Airmail at an additional cost of 45% of the total printing charge.

Cost of additional reprints

Pages	**50**	**100**	**150**	**200**
2-4	$64.00	$76.00	$89.00	$100.00
5-8	71.00	91.00	110.00	129.00
9-12	77.00	111.00	139.00	167.00
13-16	86.00	123.00	156.00	190.00
17-20	98.00	146.00	190.00	234.00
21-24	105.00	161.00	214.00	267.00
add'l 4 pgs	21.00	39.00	55.00	71.00
Covers	93.00	105.00	123.00	140.00

Charges (please compute)

_______ Quantity $ _____________
Covers $ _____________
Subtotal $ _____________
GST (7% for Canadian destinations only) $ _____________
Non-U.S. Shipping $ _____________
(Non-U.S./non-Canada orders add 45% to subtotal)

TOTAL DUE (US $) $ _____________

Send reprints to:

____
____
____
____
____

Phone* ________________________ Fax ____________________

E-mail* ____

Billing Instructions (Institutional Orders Only)

Institution ____

Street ____

City _______________________ State _____ Zip ______________

Country ________________________________

E-mail ____

* Please include telephone/e-mail in case we need to contact you about your order.

MAKE CHECKS AND PURCHASE ORDERS PAYABLE TO: The University of Chicago Press

All orders must be accompanied by one of the three payment options (purchase order, check/money order, or Visa/MasterCard):

1) Institutional Purchase Order No. _________________________________ Purchase Order attached ( ) to come ( )

order will not be processed without a number

2) ( ) Check or Money Order for total charges is attached **OR** **3)** Please charge to: ( ) VISA ( ) MASTERCARD

Cardmember name as it appears on card (please print clearly) ____

Card Number ____ Expiration Date ________________________________

Signature ____ Phone ____

RETURN THIS REPRINT ORDER FORM **WITH YOUR PROOFS** (Airmail if non-U.S.) TO:

THE JOURNAL OF GEOLOGY
Hinds Geophysical Laboratory
5734 South Ellis Avenue
Chicago, IL 60637 USA

Telephone: (773) 702-7896
Fax: (773) 702-9505
E-mail: jgeology@geosci.uchicago.edu

REPRINT INSTRUCTIONS:

DO NOT DELAY ORDERING YOUR REPRINTS Orders must be in hand before the issue goes to press.

DELIVERY AND INVOICES Reprints are shipped 2-4 weeks after publication of the Journal. Invoices are mailed at the time of shipment. **For all orders charged to institutions, an official Purchase Order must be in hand before the reprint shipment can be released.** Reprint orders payable by individuals must be accompanied by advance payment by check, Money Order, Visa, or MasterCard. In case of non-U.S. purchases, this payment must be made in the form of a check payable in U.S. currency via an American bank. Terms are net 30 days.

THE JOURNAL OF GEOLOGY

PAGE CHARGES

To encourage the widest possible distribution of the Journal by keeping subscription costs low, we charge

$70.00 per *Journal* page

Papers in excess of 22 printed pages are assessed an additional $30.00 per excess page.

Please indicate your payment below, and an invoice will be sent to you about the time the *Journal* issue appears. Please advise if there is any special procedure required for billing.

( ) I can pay page charges for my article.

( ) I request a partial waiver from page charges and can contribute $ _________ for my article. (Minimum contribution is $300.00, U.S. funds only.)

( ) I request a full waiver from page charges–please state reason: (Please note: authors granted full waivers do not receive free reprints.)

____

____

____

Author(s) Signature(s) ____ Date____________
(Author signature and date is required)

MAKE CHECKS AND PURCHASE ORDERS PAYABLE TO: The University of Chicago Press

Payment for page charges must be made in the form of one of three payment options (purchase order, check/money order, or Visa/MasterCard)

1) Institutional Purchase Order No. _________________________ attached ( ) to come ( )

Purchase order will not be processed without a number. Please list vendor as The University of Chicago Press, 11030 Langley Avenue, Chicago, Illinois 60623. If the purchase order is sent separately from this form, it must be marked "confirming" and mailed to: *THE JOURNAL OF GEOLOGY*, Hinds Geophysical Laboratory, 5734 S. Ellis Avenue, Chicago, Illinois 60637 (USA). All purchase orders must include: the name of the journal; the issue date (month and year); the author's name; the amount of the invoice.

2) ( ) Check or Money Order is attached OR 3) Please charge to: ( ) VISA ( ) MASTERCARD

Cardmember name as it appears on card (please print clearly)

____

Card Number ____ Expiration Date ______________

Signature ____ Phone ________________________

E-mail ____